ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

CO_2 CAPTURE AND STORAGE IN GEOLOGIC STUDIES IN TERMS OF ENERGY, ECONOMIC, AND ENVIRONMENTAL EFFECTS

M.Sc. THESIS

Mohammadreza JABBARI SAHEBARI

Department of Geological Engineering

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Mohammadreza JABBARI SAHEBARI
(505191340)

Department of Geological Engineering

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Thesis Advisor: Prof. Dr. Nilgün OKAY

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ENERJİ, EKONOMİ VE ÇEVRESEL ETKİLER AÇISINDAN JEOLOJİK ÇALIŞMALARDA CO_2 YAKALAMA VE DEPOLAMA

YÜKSEK LİSANS TEZİ

Mohammadreza JABBARI SAHEBARI
(505191340)

Jeoloji Mühendisliği Anabilim Dalı

Jeoloji Mühendisliği Programı

Tez Danışmanı: Prof. Dr. Nilgün OKAY

ŞUBAT 2024

Mohammadreza JABBARI SAHEBARI, a M.Sc. student of ITU Graduate School, student ID. 505191340, successfully defended the thesis/dissertation entitled "CO_2 Capture and Storage in Geologic Studies in Terms of Energy, Economic, And Environmental Effects", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Prof. Dr. Nilgün OKAY** İstanbul Technical University	.....
Jury Members :	**Prof. Dr. Şükrü ERSOY** Yıldız Technical University	.....
	Prof. Dr. Fatma GÜLMEZ YILDIRIM Istanbul Technical University	.....

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To My Loved Ones,

This thesis is dedicated to my wife, Shirin, whose unwavering support has been my guiding light. As we mark our 10th anniversary, her faith in me has made this work a testament to our love. I am deeply grateful to our families, whose love transcends distance, providing strength and unity. My heartfelt thanks also go to our friends, who have become our chosen family. This work is dedicated to all of you as a symbol of my gratitude and love.

FOREWORD

As we confront the urgent challenges posed by significant climatic shifts, a result of centuries of industrialization and relentless carbon emissions, the quest for sustainable and innovative solutions becomes paramount. My M.Sc. thesis, titled "CO_2 Capture and Storage in Geologic Studies in Terms of Energy, Economic, And Environmental Effects," aims to contribute to the critical research and development efforts in geological engineering. This work seeks to mitigate the impacts of climate change through the exploration of Carbon Capture and Storage (CCS) technologies, evaluating their viability from geological, economic, and environmental perspectives.

Undertaken at Istanbul Technical University, a bastion of excellence in engineering and environmental sciences, this thesis is positioned at the intersection of scholarly discourse and practical application in the fight against climate change. It aligns with global sustainable development goals and the imperative to reduce anthropogenic emissions, challenges that define our era.

This research delves into the Bell Creek Oil Field case study to shed light on the practical applications and inherent challenges of CCS technology. Through rigorous analysis, simulation, and modeling, the work presented aims to elucidate the potential and limitations of CCS in enhancing energy efficiency and minimizing environmental impacts.

I extend my deepest gratitude to Prof. Dr. Nilgün Okay for her invaluable guidance and mentorship throughout this endeavor. Her expertise and insights have been pivotal to the direction and success of this research.

Special thanks also go to Dr. Yahya Sorkhe, whose unwavering support and assistance were instrumental in the completion of this thesis. His encouragement and contributions have been a source of motivation and have significantly enriched this academic pursuit.

As the world grapples with the complexities of climate change mitigation, it is through the dedication and innovation of the research community that we can foster hope for a sustainable future. This thesis represents not only a significant milestone in my academic journey but also contributes to the broader goal of advancing CCS technologies and strategies for a more sustainable planet.

We find ourselves at a critical juncture in the fight against climate change. It is through pioneering research and collaborative efforts that we can aspire to turn the tide. I am grateful for the opportunity to contribute to this crucial field of study and look forward to the impact this work may have on the development of effective CCS solutions worldwide.

February 2024

Mohammadreza JABBARI SAHEBARI
(Geological Engineer)

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ABBREVIATIONS

BECCS : Bioenergy with Carbon Capture and Storage
CCS **:** Carbon Capture and Storage
CCUS **:** Carbon Capture Utilization
CH_4 **:** Methane
CO_2-ESG **:** CO_2 Enhanced Shale Gas Recovery
CO_2 **:** Carbon Dioxide
COP **:** Conference of the Parties
CSEGR **:** CO_2 Storage with Enhanced Gas Recovery
CVFE **:** Control Volume Finite Element
DAC **:** Direct Air Capture
EOR **:** Enhanced Oil Recovery
EU **:** European Union
FD **:** Finite Difference
GHG **:** Greenhouse Gas
IPCC **:** Intergovernmental Panel on Climate Change
LSLF **:** Lower Silurian Longmaxi Formation
R&D **:** Research and Development
SDG **:** Sustainable Development Goals
TP-DK **:** Triple Porosity, Dual Permeability
UNFCCC **:** United Nations Framework Convention on Climate Change

SYMBOLS

°C	**:** Degrees Celsius
%	**:** Percentage
Gt	**:** Gigatonnes
$GtCO_2$	**:** Gigatonnes of carbon dioxide
Kg/s	**:** Kilograms per second
Kt	**:** Kilotonnes
$KtCO_2$	**:** Kilotonnes of carbon dioxide
m	**:** Meters
$MtCO_2$	**:** Megatonnes of carbon dioxide
Mwe	**:** Megawatt electrical

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CO_2 CAPTURE AND STORAGE IN GEOLOGIC STUDIES IN TERMS OF ENERGY, ECONOMIC, AND ENVIRNMENTAL EFFECTS

SUMMARY

The urgency to mitigate anthropogenic climate change has never been more pressing, with the Intergovernmental Panel on Climate Change (IPCC) underscoring the critical need for rapid and significant reductions in greenhouse gas emissions to limit global warming to well below 2 °C, preferably to 1.5 °C, compared to pre-industrial levels. Among the plethora of strategies proposed to combat climate change, Carbon Capture and Storage (CCS) emerges as a pivotal technology, offering a pathway to significantly reduce CO_2 emissions from industrial sources and the atmosphere. This master's thesis delves into the exploration of CCS technology within the Bell Creek Oil Field, presenting a nuanced examination of its geological, environmental, and energy consumption dimensions, thereby contributing to the discourse on CCS as a viable climate change mitigation strategy.

The thesis is anchored in the premise that understanding the intricate interplay between geochemical alterations induced by CO_2 storage and their subsequent effects on geological parameters such as porosity, permeability, and leakage potential is crucial for assessing the feasibility, sustainability, and efficacy of CCS projects. Employing a mixed-method approach, the research integrates a comprehensive literature review, advanced reservoir simulation techniques, geochemical analysis, and energy consumption modeling to illuminate the complexities of implementing CCS within the Bell Creek Oil Field.

A pivotal aspect of the thesis is the meticulous documentation of how the injection of CO_2 into the Bell Creek Oil Field initiates geochemical processes that significantly influence the structural integrity of the storage reservoir. These geochemical reactions, such as the dissolution of silicate minerals and the formation of carbonate minerals, are shown to play a critical role in the long-term stability and capacity of the reservoir for carbon sequestration. However, they also have the potential to alter reservoir porosity and permeability, impacting fluid flow dynamics and the efficiency of CO_2 storage. The thesis underscores the necessity of selecting injection sites with favorable geological formations for CO_2 mineralization and storage integrity.

Moreover, the research rigorously evaluates the energy requirements associated with CCS operations, revealing a nuanced relationship between the technological needs for CO_2 injection and the operational efficiency. The escalating energy demands over time, necessitated by changes in reservoir characteristics such as decreasing porosity and permeability, are critical for forecasting the long-term sustainability and economic

viability of CCS projects. This analysis underscores the importance of integrating energy efficiency measures and innovative technologies to optimize CCS operations.

Environmental considerations and risk mitigation form another cornerstone of the thesis. Through detailed examination, the research highlights the critical importance of continuous monitoring and robust engineering controls to mitigate the risk of CO_2 leakage. The potential environmental impacts, including risks to groundwater quality and unintended greenhouse gas emissions, necessitate a proactive approach to reservoir management and leakage prevention.

In synthesizing these findings, the thesis presents significant implications for the strategic planning and deployment of CCS technologies. It provides a solid foundation for informed decision-making and the optimization of CCS operations, advocating for continued advancement in our understanding of subsurface processes, improvement in the accuracy of predictive models, and exploration of innovative solutions to enhance the efficiency, safety, and sustainability of CCS.

This thesis represents a contribution to the field of CCS research, providing a holistic view of the challenges and opportunities associated with the implementation of CCS technologies. Its findings underscore the complexity of CCS operations and the critical need for a multidisciplinary approach to optimize its potential benefits. As the world strives to mitigate the impacts of climate change, the insights from this research illuminate the path forward, guiding the development of effective, efficient, and environmentally responsible CCS strategies. The thesis not only advances academic knowledge but also serves as a beacon for policymakers, industry stakeholders, and researchers in the collective pursuit of sustainable and impactful climate change solutions.

ENERJİ, EKONOMİ VE CEVRESEL ETKILER ACISINDAN JEOLOJİK CALIŞMALARDA CO_2 YAKALAMA VE DEPOLAMA

ÖZET

Antropojenik iklim değişikliğiyle mücadele, bugün dünyanın karşı karşıya olduğu en büyük zorluklardan biridir. Bu mücadelenin en ön cephesinde, sanayi kaynaklı ve atmosferik CO_2 emisyonlarını önemli ölçüde azaltma potansiyeline sahip olan Karbon Yakalama ve Depolama (CCS) teknolojisi bulunmaktadır. IPCC (Hükümetlerarası İklim Değişikliği Paneli), küresel ısınmanın endüstri öncesi seviyelere kıyasla 2°C'nin, ideal olarak ise 1.5°C'nin altında tutulması gerektiğini vurgulayarak, bu teknolojinin önemini daha da artırmıştır. Bu vurgu, iklim değişikliğiyle mücadelenin sadece gelecekteki bir hedef olmaktan çıkıp, acil ve ivedi bir eylem planının gerekliliğini ortaya koymaktadır.

Günümüzde, fosil yakıtların yoğun kullanımı sonucu atmosfere salınan karbondioksit miktarı, gezegenimizin doğal dengesini tehdit eder hale gelmiştir. Bu bağlamda, CCS teknolojisi, CO_2 emisyonlarını etkili bir şekilde azaltarak iklim değişikliğinin olumsuz etkilerini minimize etme potansiyeline sahiptir. Bu teknoloji, atmosfere salınmadan önce CO_2 'in yakalanmasını, daha sonra yer altında güvenli bir şekilde depolanmasını içermektedir. IPCC'nin son raporları, küresel sıcaklık artışını sınırlandırmak için CO_2 emisyonlarının acilen ve keskin bir şekilde azaltılması gerektiğine dikkat çekmektedir. Bu, özellikle enerji üretimi, çimento ve çelik üretimi gibi yüksek karbon salınımına sahip sektörler için geçerlidir.

Karbon Yakalama ve Depolama (CCS) teknolojisinin artan önemi, yalnızca iklim değişikliğiyle mücadeledeki potansiyelinden değil, aynı zamanda fosil yakıtların yarattığı çevresel baskıları hafifletme kapasitesinden de kaynaklanmaktadır. Küresel enerji talebinin büyük bir kısmı halen fosil yakıtlardan karşılanmakta olup, yenilenebilir enerji kaynaklarının geliştirilmesi ve entegrasyonu zaman ve kaynak gerektiren bir süreçtir. Bu bağlamda, CCS, mevcut enerji sistemlerimizin karbon ayak izini azaltırken, yenilenebilir enerjiye geçiş için gerekli zamanı sağlayabilir. Bu teknoloji, atmosferdeki karbonun önemli bir kısmını etkili bir şekilde izole ederek, küresel ısınma üzerindeki baskıyı azaltma potansiyeline sahiptir. Ayrıca, enerji güvenliği ve sürdürülebilirliği açısından da stratejik bir öneme sahiptir.

Paris Anlaşması'nın küresel ısınmayı 2°C'nin altında tutma hedefine ulaşmak için, dünya genelinde karbon emisyonlarının önemli ölçüde azaltılması gerekmektedir. CCS teknolojisi, bu hedefe ulaşmada kilit bir rol oynayabilir. Enerji sektörü, sanayi üretimi ve atık yönetimi gibi çeşitli alanlarda uygulanabilirliği sayesinde, CCS, geniş bir yelpazede karbon azaltımı sağlama potansiyeline sahiptir.

CCS teknolojisinin geniş çapta benimsenmesinin önündeki en büyük engellerden biri, yüksek maliyetler ve teknik zorluklardır. Karbon yakalama süreçleri, enerji yoğun işlemler olup, özellikle enerji santralleri ve endüstriyel tesislerde büyük ölçekli uygulamaları karmaşık teknik zorluklar içermektedir. Ek olarak, depolanan karbonun uzun vadeli güvenliği ve çevresel etkileri konusunda toplum içinde ve bilim dünyasında devam eden tartışmalar bulunmaktadır. Bu zorlukların üstesinden gelmek için, CCS teknolojisine yönelik inovasyonları teşvik eden politikaların yanı sıra, kamuoyunun bilgilendirilmesi ve katılımının artırılması gerekmektedir.

Uluslararası işbirliği, CCS teknolojisinin geliştirilmesi ve uygulanmasında hayati bir rol oynamaktadır. Karbon emisyonlarının azaltılması küresel bir çaba gerektirdiğinden, ülkeler arası teknoloji transferi, bilgi paylaşımı ve finansal kaynakların mobilizasyonu gibi konularda işbirliği yapılması önemlidir. Bu işbirliği, gelişmiş ve gelişmekte olan ülkeler arasındaki teknolojik ve ekonomik uçurumu kapatmaya yardımcı olabilir, böylece küresel ölçekte daha adil ve kapsayıcı bir karbon azaltım stratejisi geliştirilebilir.

Bu çalışma, Bell Creek Petrol Sahası'nda uygulanan Karbon Yakalama ve Depolama (CCS) teknolojisini derinlemesine incelemekte ve bu teknolojinin iklim değişikliğiyle mücadeledeki potansiyelini detaylı bir şekilde ele almaktadır. CCS'in, özellikle endüstriyel emisyonların yüksek olduğu bölgelerde, atmosfere serbest bırakılan karbondioksit miktarını azaltmada etkili bir yöntem olabileceği öngörülmektedir. Bu tez, Bell Creek Petrol Sahası'nda gerçekleştirilen CCS uygulamalarının, geniş çaplı bir karbon yönetim stratejisinin önemli bir parçası olarak nasıl işlev görebileceğini göstermektedir. Bu araştırma, saha özelindeki CCS uygulamalarının karşılaştığı zorlukları ve bu teknolojinin potansiyel fırsatlarını kapsamlı bir şekilde ele alarak, CCS teknolojilerinin daha geniş bir perspektiften değerlendirilmesine olanak tanımaktadır.

Bu tez çalışması, CCS teknolojilerinin karşılaştığı teknik, finansal ve çevresel zorlukları detaylı bir şekilde incelerken, bu zorlukların üstesinden gelinmesi için gereken stratejileri ve politikaları da tartışmaktadır. CCS operasyonlarının başarılı bir şekilde uygulanabilmesi için gerekli olan disiplinler arası işbirliğinin ve kapsamlı bir planlamanın altını çizmektedir. Özellikle, CCS teknolojisinin enerji sektöründe ve ağır sanayide nasıl entegre edilebileceği üzerinde durularak, bu teknolojinin geniş kapsamlı iklim politikalarındaki yerine dair önemli bilgiler sunulmaktadır. Ayrıca, CCS uygulamalarının optimizasyonu ve sürdürülebilirliği konusunda bilgilendirilmiş kararlar alınabilmesi için gerekli olan çok boyutlu analizlerin ve değerlendirmelerin yapılmasının önemine vurgu yapılmaktadır.

Bu çalışma aynı zamanda, CCS teknolojilerinin etkili bir şekilde uygulanabilmesi için gelişmiş simülasyon tekniklerinin, jeokimyasal analizlerin ve enerji tüketimi modellemesinin önemini de ele almakta, Bell Creek Petrol Sahası'ndaki uygulamalardan elde edilen veriler ışığında genel bir çerçeve sunmaktadır. Bu analizler, CCS teknolojisinin karşı karşıya olduğu zorluklara çözüm bulma ve bu teknolojinin uygulanabilirliğini artırma yönünde kritik bir rol oynamaktadır. Karbon yakalama ve depolamanın etkinliğini maksimize etmek ve olası çevresel riskleri minimize etmek için, saha bazlı uygulamalardan elde edilen verilerin ve tecrübelerin geniş çapta paylaşılmasının önemi de bu tezde vurgulanmaktadır.

Bu detaylı araştırma, Karbon Yakalama ve Depolama (CCS) sürecinin, özellikle CO_2 'in yer altı depolanması esnasında meydana gelen jeokimyasal değişikliklerin, yer altı yapısının temel özellikleri üzerinde nasıl karmaşık etkileşimler yarattığını inceliyor.

Bu sürecin, jeolojik formasyonların porozitesi, geçirgenliği ve sızıntı riski gibi kritik parametreler üzerindeki etkilerini anlamak, CCS projelerinin başarısını belirleyen temel faktörler arasında yer alıyor. Bell Creek Petrol Sahası'nda gerçekleştirilen CCS uygulaması, bu karmaşık etkileşimlerin çeşitli yönlerini aydınlatmakta ve CO_2 depolama teknolojisinin uygulanabilirliğine, sürdürülebilirliğine ve genel etkinliğine ilişkin değerli bilgiler sunmaktadır. Bu araştırma kapsamında, CO_2 'in yeraltı rezervuarlarına enjeksiyonu sonucu meydana gelen jeokimyasal reaksiyonların, mineral çözünürlüğü, asit üretimi ve bu reaksiyonların rezervuarın fiziksel özelliklerine olan etkisi gibi önemli faktörler detaylı bir şekilde ele alınmaktadır.

Bu çalışma, gelişmiş rezervuar simülasyon tekniklerinin, jeokimyasal analizlerin ve enerji tüketimi modellemesinin entegrasyonunu içermekte, bu entegre yaklaşımın CCS projelerinin geliştirilmesi ve uygulanması için kritik öneme sahip olduğunu vurgulamaktadır. Bell Creek Petrol Sahası'nda yapılan uygulamalar, CO_2 depolamanın rezervuar özellikleri üzerindeki etkisinin yanı sıra, bu sürecin enerji verimliliği ve çevresel sürdürülebilirlik açısından da değerlendirilmesine olanak tanımaktadır. Araştırma, CCS'nin etkin bir şekilde uygulanabilmesi için, yer altı jeolojisinin ve rezervuar dinamiklerinin detaylı bir şekilde anlaşılmasının yanı sıra, CO_2 enjeksiyon ve depolama işlemleri sırasında tüketilen enerjinin optimize edilmesinin de büyük önem taşıdığını göstermektedir.

Ayrıca, bu araştırma, CO_2 depolama sürecinin jeolojik parametreler üzerindeki etkilerinin, uzun vadeli rezervuar yönetimi ve sızıntı önleme stratejileri açısından kapsamlı bir değerlendirilmesini gerektirdiğini ortaya koymaktadır. Bu kapsamda, CCS teknolojisinin başarılı bir şekilde uygulanabilmesi için, yer altı rezervuarlarının jeokimyasal ve fiziksel özelliklerinin yanı sıra, CO_2 depolama sürecinin çevresel etkilerinin ve sürdürülebilirliğinin de detaylı bir şekilde incelenmesi gerekmektedir. Bell Creek Petrol Sahası'ndaki uygulamalar, CCS teknolojisinin potansiyelini maksimize etmek ve olası çevresel riskleri azaltmak için gerekli olan bilgi birikimini ve teknik uzmanlığı sağlamaktadır. Bu, CCS teknolojisinin daha geniş bir çerçevede ele alınarak, karbon emisyonlarının azaltılması ve iklim değişikliğiyle mücadelede kritik bir araç olarak kullanılmasının önünü açmaktadır.

Bu çalışmanın kapsamlı incelemesi, Karbon Yakalama ve Depolama (CCS) teknolojisinin Bell Creek Petrol Sahası'nda nasıl hayati jeokimyasal değişikliklere neden olduğunu detaylandırmaktadır. Özellikle, CO_2 'in sahaya enjekte edilmesiyle tetiklenen jeokimyasal süreçlerin, depolama rezervuarının yapısal bütünlüğü üzerinde derin etkileri olduğu gözlemlenmiştir. Bu süreçler, CO_2 'in yer altı kayaçlarıyla etkileşime girerek mineral tuzaklamasını teşvik ederken, aynı zamanda rezervuarın porozitesi ve geçirgenliği gibi temel özelliklerinde de değişikliklere yol açabilmektedir. Bu jeokimyasal reaksiyonlar, karbon dioksitin yer altında kalıcı olarak saklanmasına imkan tanırken, saklama kapasitesi ve etkinliği üzerinde de önemli bir rol oynamaktadır. Bu bağlamda, araştırma, CO_2 depolama süreçlerinin optimizasyonu için uygun jeolojik formasyonların seçilmesinin ve rezervuarın jeokimyasal uyumluluğunun sağlanmasının kritik önem taşıdığını vurgulamaktadır.

Araştırma, CO_2 enjeksiyonunun rezervuarın porozite ve geçirgenlik özelliklerinde meydana getirdiği değişimleri incelerken, bu değişimlerin CCS teknolojisinin verimliliğine ve çevresel sürdürülebilirliğine olan etkilerini de göz önünde bulundurmaktadır. Bu sürecin, yer altı sıvı akış dinamiklerini nasıl etkilediği ve CO_2 depolama işlemlerinin uzun vadeli başarısı için gerekli olan rezervuar yönetimi stratejilerine nasıl katkıda bulunabileceği üzerinde durulmaktadır.

Özellikle, CO_2 mineral tuzaklaması yoluyla nasıl güvenli bir şekilde yer altında hapsedildiğini ve bu sürecin yer altı su kaynakları üzerindeki potansiyel etkilerini azaltma potansiyelini ele almaktadır. Bu, CCS uygulamalarının çevresel etkilerini en aza indirgeyerek, karbon emisyonlarının azaltılması ve küresel ısınma ile mücadelede önemli bir rol oynayabileceğini göstermektedir.

Son olarak, bu çalışma, CCS teknolojisinin uygulanabilirliğini artırmak ve CO_2 depolama süreçlerinin etkinliğini maksimize etmek için, kapsamlı jeokimyasal modelleme ve rezervuar simülasyonlarının entegre edilmesinin önemini vurgulamaktadır. Bu entegrasyon, CCS projelerinin planlanması ve yönetilmesinde bilinçli kararlar alınmasını sağlayarak, potansiyel jeokimyasal risklerin proaktif bir şekilde yönetilmesine olanak tanımaktadır. Böylece, CCS teknolojisinin Bell Creek Petrol Sahası gibi alanlarda başarıyla uygulanabilmesi için gerekli olan teknik ve çevresel bilgi birikiminin derinleştirilmesine katkıda bulunmaktadır. Bu yaklaşım, CCS'in küresel karbon yönetimi stratejilerinde etkili bir araç olarak rol almasını destekleyerek, iklim değişikliğiyle mücadelede önemli bir adım oluşturmaktadır.

Bu kapsamlı çalışma, Karbon Yakalama ve Depolama (CCS) operasyonlarının enerji tüketimini detaylı bir şekilde ele alarak, CO_2 enjeksiyon sürecinin teknik gereksinimleri ile operasyonel verimliliği arasındaki ince dengeyi vurgulamaktadır. Enerji tüketimi, CCS projelerinin tasarım ve uygulama aşamalarında kritik bir değişken olarak öne çıkmakta; çünkü CO_2 'in yeraltına etkin bir şekilde enjekte edilmesi ve saklanması, önemli miktarda enerji gerektirmektedir. MATLAB yazılımı kullanılarak gerçekleştirilen simülasyonlar, rezervuarın fiziksel ve jeolojik özelliklerinde meydana gelen değişikliklerin - özellikle porozitenin azalması ve geçirgenliğin düşmesi gibi - zamanla enerji ihtiyacını nasıl artırdığını gözler önüne sermektedir. Bu simülasyon sonuçları, CCS teknolojisini etkin bir şekilde uygulamak için gerekli olan enerji miktarının, projenin başlangıcından itibaren dikkatlice hesaplanması ve yönetilmesi gerektiğini göstermektedir.

Araştırma ayrıca, CCS operasyonlarının enerji verimliliği üzerine odaklanarak, CO_2 'in yeraltı depolama işlemlerinin optimize edilmesinde kullanılan tekniklerin enerji tüketimi üzerindeki etkilerini de analiz etmektedir. Bu bağlamda, enerji tüketiminin azaltılması ve operasyonel verimliliğin artırılması amacıyla, enjeksiyon prosedürlerinde yenilikçi tekniklerin ve malzemelerin kullanımının önemi vurgulanmaktadır. Enerji tüketimi analizleri, CCS projelerinin çevresel ayak izini ve işletme maliyetlerini düşürmeye yönelik stratejik planlamada kritik bir rol oynamaktadır.

Bu çalışma, CO_2 depolama projelerinin başarısı ve bütünlüğünün sağlanmasında erken tespit sistemlerinin ve adaptif yönetim stratejilerinin geliştirilmesinin önemini de ortaya koymaktadır. CCS operasyonları sırasında karşılaşılabilecek olası sorunların proaktif bir şekilde tespit edilip yönetilmesi, projenin uzun vadeli sürdürülebilirliği ve başarısını destekleyen temel unsurlardandır. Örneğin, rezervuarın geçirgenliğindeki azalma veya porozitedeki düşüş gibi değişiklikler, CO_2 saklama kapasitesini ve verimliliğini etkileyebilir; bu nedenle, bu tür değişiklikleri erken aşamada tespit edebilen sistemlerin ve stratejilerin geliştirilmesi büyük önem taşımaktadır.

Bu çalışma, çevre politikaları ve risk yönetimi alanında kapsamlı bir analiz sunarak, Karbon Yakalama ve Depolama (CCS) teknolojilerinin uygulanmasında karşılaşılan temel çevresel riskleri ve bu risklerin azaltılmasına yönelik stratejileri derinlemesine inceler. Çevresel sürdürülebilirlik, iklim değişikliğiyle mücadelede önemli bir rol oynarken, CCS uygulamaları sırasında potansiyel CO_2 sızıntılarının önlenmesi ve

minimize edilmesi, projelerin başarısını doğrudan etkileyen kritik bir faktördür. Bu bağlamda, sürekli izleme sistemleri ve güçlü mühendislik kontrolleri, sızıntı risklerini azaltmak için vazgeçilmez yöntemler olarak öne çıkmakta; bu yöntemler, rezervuar bütünlüğünü korumak, çevresel etkileri en aza indirmek ve toplumsal kabulü artırmak amacıyla gelişmiş teknolojilerin ve best practices'in entegre edilmesini gerektirmektedir.

Ayrıca, bu araştırma, karşılaşılan çevresel zorlukların üstesinden gelmek için çok yönlü politikaların ve yönetmeliklerin geliştirilmesinin yanı sıra, çevresel izleme ve risk değerlendirme protokollerinin standartlaştırılmasının önemini vurgulamaktadır. Etkili bir çevre yönetim sistemi, potansiyel CO_2 sızıntıları ve diğer olası çevresel etkilerin erken tespit edilmesini sağlayarak hızlı müdahale ve mitigasyon stratejilerinin uygulanmasını kolaylaştırır. Bu, CCS projelerinin çevresel ve toplumsal açıdan kabul edilebilirliğini artırmak için kritik öneme sahiptir.

Bu tez aynı zamanda, CCS teknolojilerinin uygulanması sırasında karşılaşılabilecek çevresel risklerin azaltılmasında proaktif yaklaşımların benimsenmesi gerektiğini belirtmektedir. Risk azaltma stratejileri arasında, rezervuar seçimi, tasarım aşamasında çevresel duyarlılık analizleri yapmak, operasyonel güvenlik standartlarını yükseltmek ve acil durum müdahale planlarını güncellemek yer almaktadır. Bu yaklaşımlar, CCS projelerinin çevresel etkilerini en aza indirgeyerek, genel sürdürülebilirlik hedeflerine katkıda bulunacak ve iklim değişikliği ile mücadelede önemli bir araç olacaktır.

Son olarak, bu araştırma, iklim değişikliği ile mücadelede CCS'nin rolünü güçlendirmek için bilimsel topluluk, politika yapıcılar, endüstri liderleri ve kamuoyu arasında etkili bir iletişim ve işbirliğinin önemini vurgulamaktadır. CCS teknolojilerinin başarılı bir şekilde uygulanabilmesi için, çevresel risklerin yönetilmesi ve azaltılması konusunda kapsamlı bilgi paylaşımı ve toplumsal farkındalığın artırılması gerekmektedir. Bu, hem politika yapıcıların hem de endüstri paydaşlarının, sürdürülebilir ve etkili iklim değişikliği çözümlerini desteklemek ve teşvik etmek için birlikte çalışmasını sağlayacaktır.

1. INTRODUCTION

The change in climatic conditions is primarily due to anthropogenic activities like emissions due to utilization of uncontrolled fossil fuel, industrial, land use and land conversion sources participating in climate deterioration (Policy and Evaluation, 1999; Crowley, 2000; Review; 2001; Alley et al., 2003). These activities causing to produce notorious gases called Greenhouse Gases (GHG's) which are capable of accumulating and holding energy in the atmospheric layers and resulting in the Earth temperature rise.

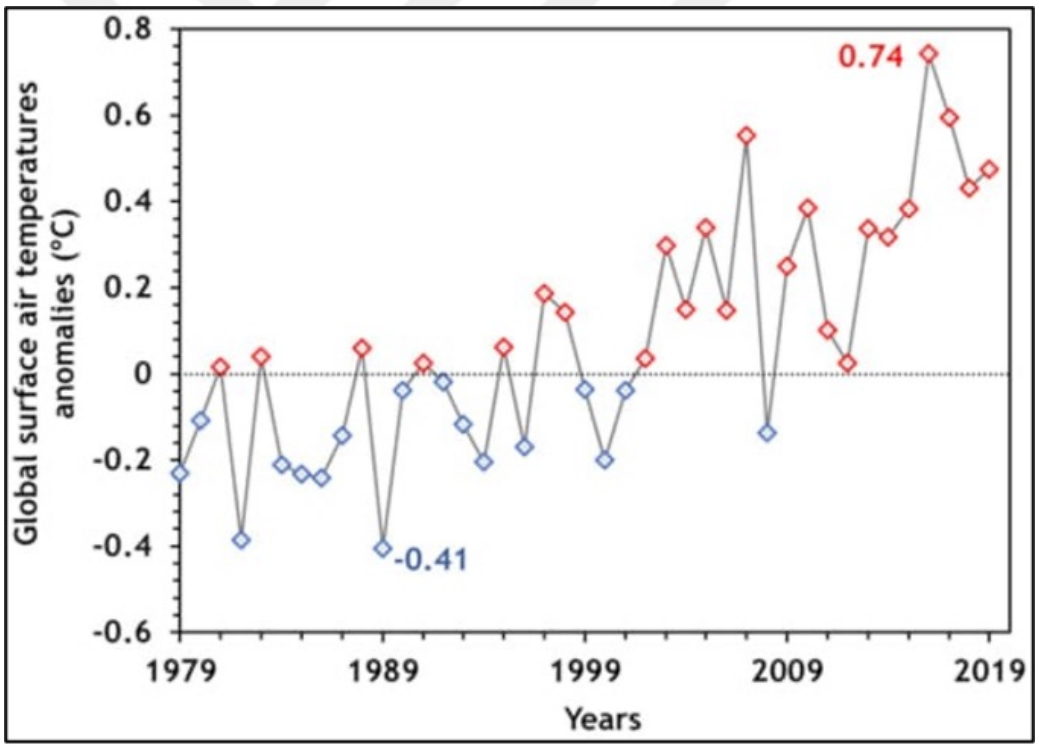

Figure 1.1. Atmospheric temperature anomalies for the period of 1970-2020 (Service, 2019).

The climate change, increasing unexpected weather conditions and intense impacts has forced the policy makers and scientist to stop and have thought that how these consequences can be mitigated without compromising the demand of modern world. The impacts of climate change as the consumption of natural resources to produce

energy was resulting in the release of various pollutants like Carbon Dioxide, Carbon Monoxide, Oxides of Sulfur, Oxides of Nitrogen, Green House Gases other than CO_2 and organic pollutants. The release of these pollutants into the atmosphere initiated the chain of unstoppable reactions contaminating the environment. The one of the most important pollutants which concentration has been increased drastically since industrial revolution is carbon dioxide for which the world is most concerned.

The emissions in the form of Carbon Dioxide (CO_2) play a major role in extended global concerns with considerable outcomes in near future. The peculiar behavior of carbon dioxide is trapping heat with maximum capacity bestowed this chemical specie as potential threat to global ecosystem. With regards to the estimations, CO_2 emissions in 2020 and 2030 will be 36.8 Gt and 42.9 Gt, respectively, 73% and 102% greater than in 1990 **(**Figure 1.2**)**. Energy combustion and industrial processes increased the global emission of CO_2 in 2021 as the year with the highest CO_2 emission in history (Davis et al., 2010).

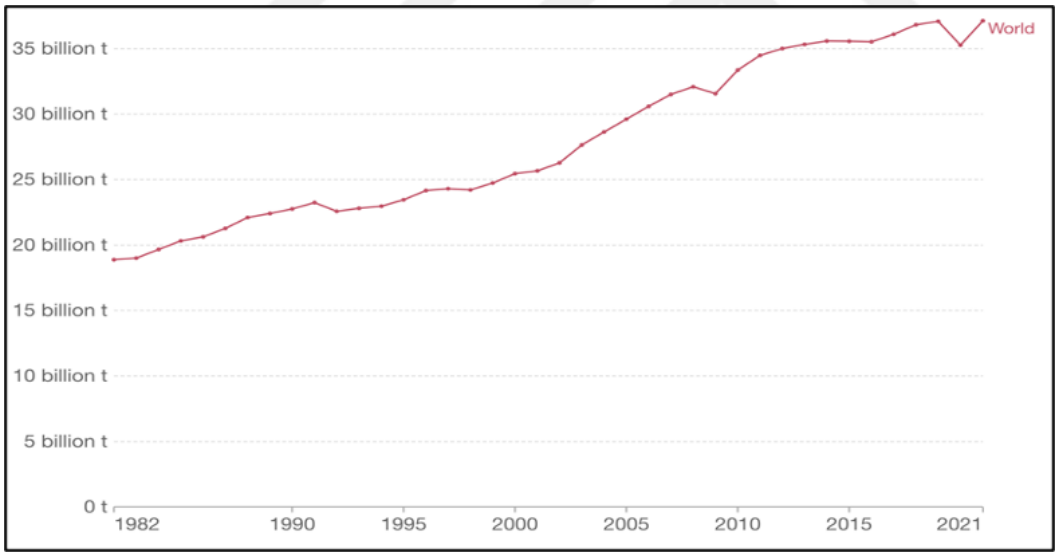

Figure 1.2. Increase in CO_2 emissions (Friedlingstein, 2022).

Increased emission of greenhouse gases in 2021 nullified the COVID-19-induced decrease in emission in 2020 by over 1.9 Gt (Al Hameli et al., 2022).

The climate experts shown consent on the limiting the increasing temperature no more than 1.5 ºC - 2 ºC for the sake of safety of earth and its inhabitants. The recorded increase in atmospheric temperature and even expected threshold can cause potential impacts on the climate and livings beings and can be seen in the form of frequent and

intense storms, severe heat waves, forest fires, precipitation, droughts and heavy rainfall resulting in flooding, high sea level, threats to biodiversity, human health concerns and increasing global market and government concerns to resources are few mentioned impacts (Peridas, 2021).

1.1. Global Goals and Mitigation of Anthropogenic Emissions

Acknowledging the critical rise in atmospheric carbon dioxide (CO_2) levels due to human activities like fossil fuel burning and deforestation, it is urgent to address climate change. This surge in CO_2, a principal driver of global warming and ocean acidification, necessitates a focused discourse on mitigating its profound impacts on the global climate system. The importance of this issue has spurred extensive research and policy dialogues aimed at formulating effective climate action strategies. It is essential to bridge this understanding of climate change dynamics with the broader objectives of the Sustainable Development Goals (SDGs) and the Net Zero Emissions (NZE) ambition.

The interplay between CO_2 emissions and sustainable development underscores the necessity for integrated climate and policy frameworks. Research underscores the critical linkage between reducing carbon emissions and achieving the Sustainable Development Goals (SDGs), suggesting that concerted climate action is pivotal to sustainable progress (Smith et al., 2021). By aligning climate strategies with the SDGs, efforts to mitigate CO_2 impacts directly contribute to broader objectives like economic resilience and environmental sustainability (Jones and Harris, 2020). This alignment is essential for realizing the Net Zero Emissions (NZE) ambition within the context of global sustainability targets (Figure 1.3).

United Nations (UN) General Assembly adopted 'Transforming our World: the 2030 Agenda for Sustainable Development' in September 2015, a few months before the Paris Agreement for Climate Change and Sendai Risk Reduction Framework (UN, 2015). A follow-up to the Millennium Development Goals, this resolution includes 17 Sustainable Development Goals (SDGs) that address a wide range from human development issues, disasters and all types of environmental damages concerns (Table 1.1).

Table 1.1. UN Sustainable Development Goals

Goal	Title	Description
1	No poverty	End poverty in all its forms everywhere
2	Zero hunger	End hunger, achieve food security and improved nutrition and promote sustainable agriculture
3	Good health and well-being	Ensure healthy lives and promote well-being for all at all ages
4	Quality education	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5	Gender equality	Achieve gender equality and empower all women and girls
6	Clean water and sanitation	Ensure availability and sustainable management of water and sanitation for all
7	Affordable and clean energy	Ensure access to affordable, reliable, sustainable, and modern energy for all
8	Decent work and economic growth	Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all.
9	Industry, innovation, and infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
10	Reduce inequality within and among countries	Reduce inequality within and among countries.
11	Sustainable cities and communities	Make cities and human settlements inclusive, safe, resilient, and sustainable.
12	Responsible consumption and production	Ensure sustainable consumption and production patterns.
13	Climate action	Take urgent action to combat climate change and its impacts.
14	Life below water	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development.
15	Life on land	Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse.
16	Peace, justice, and strong institutions	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable, and inclusive.
17	Partnership for the goals	Strengthen the means of implementation and revitalize the global partnership for sustainable development.

The greenhouse gases' emissions in the environment and raised public concerns with their health forced the body of United Nations Framework Convention on Climate

Change (UNFCCC) in 1992 to conduct a meeting and develop the comprehensive policy on managing and reducing the emissions to protect the climate and ecosystem. Within the 2030 goals for improvement and mitigation of climate, Policy Makers from each state shown their commitment to protect the humans as well as ecosystem from destruction and complete deterioration by taking crucial steps. The goals identify that Climate Change as "one of the greatest demanding situations of our time" and concerns approximately "its detrimental influences undermine the capability of all international locations to attain sustainable development (UN, 2022). To elaborate the development goals to achieve Net Zero Emissions the United Nations categorized these goals into three categories (Figure 1.3):

1. Short Term (2015) Goals called Millennium Development Goals (MGD's) announcement of UN in international locations.
2. Technological Desires or Mid Goals (2050) for Sustainability Development of the Boards
3. Long Term Goals (Beyond 2050) regarding World State Transition for institutional affairs (Robert et al. 2005).

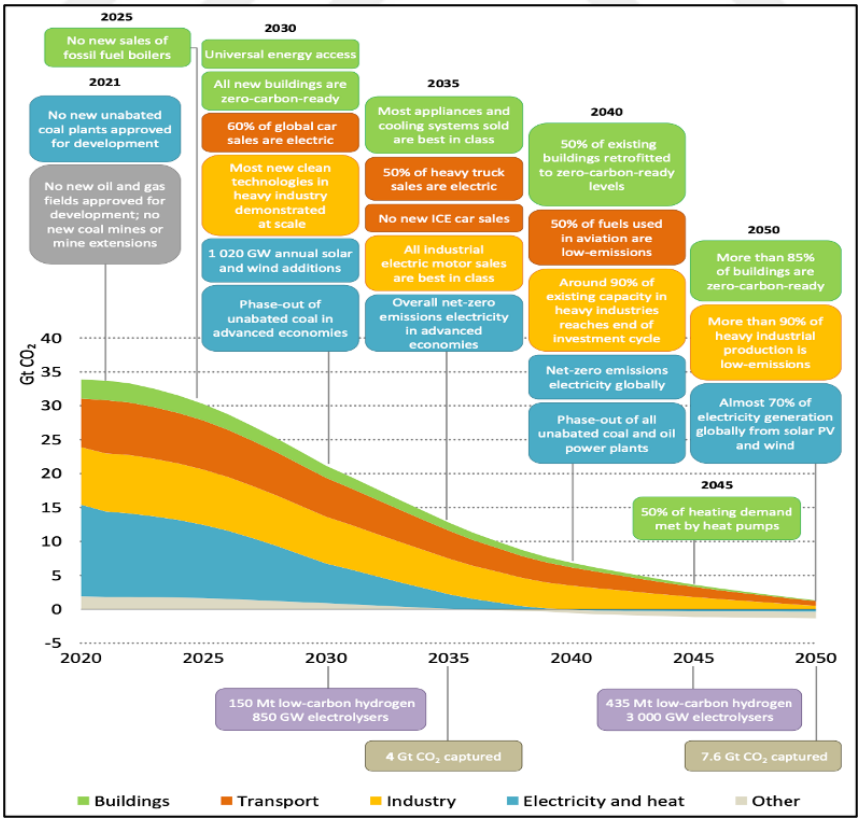

Figure 1.3. Key milestones in the pathway to Net Zero (IEA, 2021).

The Intergovernmental Panel for Climate Change (IPCC) based on scientific evidence suggested to limit the carbon emissions to bring down or slow down the global heating phenomena. The pre-commercial degrees will significantly lessen the chances of catastrophe to public health and well-being. To achieve the set goals, human need to cut their emissions by changing their behavior towards resources efficiency. Carbon Dioxide (CO_2) emissions targets aims to reduce the half of emissions as per set in 2010 goals until 2030 and completely cut the emissions to zero by 2050. The GHG effect posed by other gases ought to attain net zero soon thereafter (among 2063 and 2068).

The technologies available to reduce atmospheric carbon dioxide emissions and their contribution to achieving the SDGs and Net Zero Emission Goals have been investigated for some time (Middleton and Bielicki, 2009). Scientists across various disciplines are endeavoring to unravel the complexities of global warming. Their studies encompass industrial processes, the science of raw materials and products, environmental chemistry and pollutants, solid waste management and disposal, as well as political and social sciences.

Carbon Capture and Storage (CCS) strategies are just one example of the solutions being explored in detail to the challenge of lowering the CO_2 level and generating new green effective solutions. The 1.5-degree Celsius barrier has been established by the Conference of Parties (COP) as the upper limit of rising temperature and is regarded as necessary for supporting life on Earth. The researcher discovered CCS technology to be a dependable and efficient method of addressing the global issue of CO_2 emissions as well as net zero emission goals (Romasheva and Ilinova, 2019; Stuardi et al., 2019).

The IPCC evaluated the potential synergies and trade-offs between mitigation options and sustainable development, including using CCS in the industrial and energy sectors (IPCC, 2018). Through direct emission reductions and indirect supply of low-carbon energy, CCS can provide affordable and clean energy and support the decarbonization of industry (SDG 7). Several studies show that CCS can contribute to job retention and reduce CO_2 emissions, which can decouple economic growth from environmental degradation (SDG 8). Additionally, CCS can enhance innovation systems and reduce cities' carbon footprint to make them more sustainable (SDG 10), enabling sustainable infrastructure development (SDG 9). Consequently, developing and utilizing low-

carbon technologies comports different environmental impacts, resulting in trade-offs with the SDGs. The SDG 13 is strongly associated with the Net Zero Emission (NZE) target to obtain this intention by using 2030 and 2050. The CCS and EOR is a technique developed and researched by means of the scientist to lessen the GHG emissions inside the form of CO_2 emissions and find a way to acquire 2050 purpose.

In order to achieve 2030 goal and 2050 commitment, there is need to develop feasible and viable strategies to reduce the emissions and need to balance our environment by eliminating the CO_2 (Salas et al., 2020).

This thesis research includes literature review that the technological and scientific approach in deployment of CCS as well as political, economic and environmental issues.

The following are the objective of research work:

- Issues for CCS and EOR
- Reviewing the literature to find the potential in the site and develop a justification for the research work.
- Data for site study
- Simulation of data of site
- Geological modeling of data and results to evaluate the potential of target site.
- Geological storage site assessment and characterization
- Techno-economic analysis and optimization
- Hazards and risk associated with the study area.
- Environmental impact assessment and risk management

2. LITERATURE REVIEW

This chapter reviews the literature in context of carbon capturing, storage and utilization techniques being used by the world. The Carbon Capture, Utilization and Storage (CCUS) term was first presented in 1977 for the coal-operated plants emitted high amount of carbon dioxide (Figure 2.1). It was studied and recommended CO_2 could possibly be captured and stored into a suitable geological site (Metz et al., 2005). According to IEA statistics and data projection based on the capacity of CCUS technologies it is estimated that 17% of CO_2 can be captured and stored till 2050 using this technique.

The data statistics and results show that only CCUS can contribute to net zero emission goal by 2050 with a sole portion of 32% in reduction (Taylor, 2010). The studies also show that until 2060 almost 28 gigatons of CO_2 could be removed from the atmosphere using and implementing the CCUS on cement, chemical, and steel industries (IEA, 2019). The IEA also recommended to incorporate the CCUS technologies and strategies as a major component of policy making and implementation to overcome the global issue and mitigate the climate change problems (Metz et al., 2005). A practical application of CCS in the energy industry is Enhanced Oil Recovery (EOR).

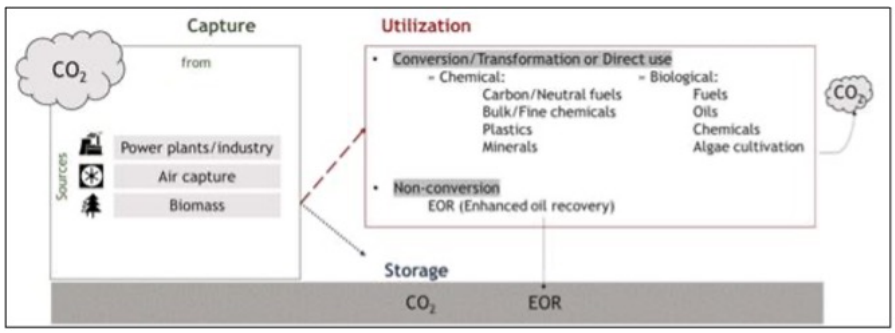

Figure 2.1. From stationary source to carbon capture, utilization and storage (Bui et al., 2018; Sekera and Lichtenberger, 2020).

2.1. Geological Aspect of CCS

The studies show the most effective CO_2 sequestration possibilities are geological capturing of emissions through mineral addition, and ocean injection. Similarly, CCS removes CO_2 from air by capturing and injecting it in deep down wells which retains and store the liquids for hundreds to thousand years. Based on research, CCS in geological formations is the best way to take up and reduce the CO_2 emissions.

The CCS system relies on trapping carbon emissions from fossil fuel-operated facilities, businesses, and natural gas reservoirs, then permanently injecting them into suitable geological basins (White et al., 2003; Holloway, 2005; Bachu et al., 2007). Many factors are considering in this process which need to be handled with care by monitoring, regulating, recording, and sustaining to guarantee that every step of the injection process is done correctly, and gas is being properly injected for years and not traveling back to the earth's surface (Metz et al., 2005).

Holt et al. (1995) conducted a study on the subterranean containment of CO_2 within aquifers and petroleum reservoirs. Their reservoir modeling of CO_2 infusion into a water-saturated oil field indicated potential for considerable oil extraction, along with substantial CO_2 storage capacity achieved via water displacement. The estimated storage potential for CO_2 sequestration in an aquifer was found to fluctuate between 13 and 68 % of pore volume, influenced by the dominant displacement processes involved.

In 1996, Norway started the Sleipner site (Capacity; 0.9 million tons per year) to use CO_2 for injection into salty underground water stream. The In-Salah geological formation in Algeria was initiated CCS technique by injecting the CO_2 into an underground aquifer having injection ability of 1.2 million tons per year (Herzog, 2016).

In Ketzin, Germany, a site was developed for the research and development for CCS strategy study named CO2SINK. The CO2SINK is run by Shell PLC which inject carbon dioxide into onshore salt aquifer. In Poland another pilot scale basin was established for Enhanced Coal Bed Methane Recovery and was first site of its nature developed to study the financial and economic factors of CO_2 capture and storage. The

site is named after the technique used for CO_2 capture and storage and called RECOPOL which means "Reduction of CO_2 with the help of coal seams of the Silesian Coal Basin in Poland" contributing to environmental sustainability (Papaspiropoulos, 2017).

The various geological formations were identified and operated which have been discussed above, there are some other worldwide established CCS projects which are currently in operation. Among them 22 basins are currently in operation at large level all over the world. There are 3 project sites which were developed, and details are given below (Papaspiropoulos, 2017):

1. Tomakomai Basin for CCS which was operated on hydrogen generation plant. The CO_2 captured and then injected to deep coastal injection facility.
2. The Illinois Project was commissioned in 2017 to store about 1 million tons per annum of CO_2 into deep salt aquifer CO_2 capturing basin. The Illinois is also the pioneer geological formation for the bioenergy carbon capturing and storage.
3. The Petra Nova Carbon Capture project having capacity of 1.4 million tons per annum in Texas, USA, is the largest basin using post combustion technique to capture the CO_2.

Carro et al. (2021) explored an energy storage mechanism utilizing supercritical CO_2 cycles and geological formations. Their research involved the creation of conceptual integration layouts, adaptable for various scenarios for carbon dioxide capture. Their findings suggest the possibility of storing over 1 Mton/year of CO_2 through this method. Particularly notable is its integration potential with high carbon-emitting industries, such as the cement or chemical sectors.

The three are commonly types of geological formations which are used for capturing CO_2:

1. Oil and gas reservoirs as geological formations.
2. Coal seams where mining is not possible.
3. Underground saline aquifers.

2.1.1. Oil And Gas Reservoirs as Geological Formations.

The Oil and Gas fields are one of the best geological formations for capturing and storing the CO_2 emissions (Damen et al., 2005). The oil and gas field reservoirs have minimum leakage risks and maximum sealing capacity for storing CO_2. The reason is that such sites have already stored oil and gas for many years without leakage and can store permanently. The second benefit is their characteristics had already been studied in detail during the installation and commissioning of site for mining which gives reliable and cost-effective approach to study the site better. If CO_2 capture is carried out using the oil and gas reservoirs, they have the potential to increase oil and gas output (according to the U.S. Geological Survey).

Pomar-Castromonte et al. (2021) investigated to assess the potential of the Pariñas Formation, located in the Talara basin, Peru, for CO_2 geological storage. The Pariñas Formation, characterized by sandstone with an average porosity of 17.6% and a horizontal permeability of 640 millidarcies. It contains several exhausted hydrocarbon reservoirs, offering conducive conditions for CO_2 geological storage. This pioneering approach in Peru opens avenues for assessing CO_2 storage potential in hydrocarbon reservoirs within the region, contributing to strategies aimed at mitigating the impacts of global change. The findings from this research estimate the storage capacity at approximately 35.37 million tons of CO_2.

Cao et al. (2022) conducted a study on numerical modeling for CO_2 storage with impurities, specifically focusing on its application in enhanced gas recovery within depleted gas reservoirs. CCS in these reservoirs is a key method for reducing CO_2 emissions. To address cost concerns and explore potential financial advantages, the study examined several critical factors included gas recovery efficiency, reservoir temperature, residual water saturation, and the rate of CO_2 injection, the use of CO_2 mixed with impurities (N_2 and O_2) in both CCS and CO_2 storage coupled with enhanced gas recovery.

Key findings revealed that the CO_2 storage capacity diminishes in line with increasing impurity concentration. Reservoirs with a temperature of 75°C were found to be more conducive to CO_2 storage than those at 114°C. It was also found that N_2 and O_2 could be detected roughly half a year ahead of CO_2 at a specific location, serving as an early warning signal for potential CO_2 leakage due to chromatographic partitioning. This

partitioning is influenced not only by the solubility and concentration of impurities but also significantly by the residual water saturation in the reservoir.

The EOR technology is frequently employed in CCS to increase oil output and extraction from oil reservoirs. The oil and gas industries are primarily using EOR to reduce CO_2 emissions and create a win-win situation for their emissions.

The carbon that is being compressed and pumped into the well site will mix with the rocky subsurface surface and harden over time, decreasing the emissions into the atmosphere. The cost savings compared to other industrial sources of CO_2 emissions and the experience gained via this carbon capturing technique also add to the attribute of oil recovery through CO_2.

The CO_2 injected into the well helps to enhance the oil and gas recovery and as a result also reduce oil and gas recovery cost as well. The enhanced oil recovery is in practice for many countries and at various sites worldwide. The CO_2 is being stored using this methodology and more than 25 million tons of CO_2 is being stored annually (Solomon et al., 2008). Permian Basin of Texas in USA contains highest number of EOR sites where the captured CO_2 is being transported to the reservoirs in Colorado, New Mexico and Wyoming through transportation facilities. The injected CO_2 into the formation will make the small amount of oil will dissolve CO_2, which will increase its density and make it more viscous, allowing it to flow smoothly to oil wells. The oil and gas reservoirs using water flooding technique gives 30-40% enhanced oil recovery, while a CO_2 reservoir can give enhanced 10-15% oil recovery.

2.1.2. Coal seams where mining is not possible.

Un-minable Coal Seams is considered as alternative way to inject the CO_2 and store into deep coal seams which are not minable for coal mining (Byrer and Guthrie, 1999). These coal mines seams are defined as the too deep or too thin mines which are difficult to mine considering the economic and technological factors limitations. Methane gas is present in coal seams at their surface, and drilling into coal seams can be used to collect this gas using CO_2. By releasing pressure or dewatering the coal seam, which releases the methane gas, it is possible to collect methane from coal bed seams. Like an oil and gas reservoir, CO_2 injection can achieve the improved methane recovery. Based on the pilot scale studies and practical feasibility studies it is seen that coal seam beds have capacity for storing CO_2 along enhanced methane gas

recovery application (Thakur et al., 2002). The few studies had been conducted on using this method to recover methane and injecting the CO_2 and results show the potential and capacities of sites for CO_2 storage and enhanced methane recovery. The thickness of coal seam bed is important factor in methane recovery as greater thickness pose greater volume for CO_2 storage and result in greater methane recovery. Another factor involves the thicker coal beds have more capacity for the technological implementation rather than thin coal beds.

Coal's substantial internal surface area enables it to store a significant volume of CO_2 within its matrix (Reisabadi et al., 2022). The interaction between matrix expansion and the orientation of horizontal CO_2 injection wells on permeability remains under-explored. The site fitness for CO_2 storage and gas recovery is based on the various factors like technical feasibility, economic factors and regulatory factors (Bachu et al., 2007; Oudinot et al., 2007). The site which is implied with the CO_2 storage should be restricted from mining or in any case if mined the stored CO_2 will again be released to the environment. The mining of un-minable coal seam bed is feasible to mine with development of technology, but it will waste all the effort and resources utilized in CO_2 storage.

2.1.3. Underground saline aquifers

Storage of CO_2 in deep salt deposits or aquifers is one of the most efficient strategies for doing so. The saline beds are the layers of rocks consist of limestone and sandstones which containing saturated solution of sodium hydroxide called brine. When compared to coal seam beds or oil and gas reservoirs, saline basins have a far wider use and are more effective at storing CO_2. This is because saline basins have a significantly higher storage capacity. The United States two-third is covered by underlying saline basins as the aquifer with saline formations is highly concentrated with salts and not fit for use for irrigation/agricultural purposes or any such use, so ground water contamination is also not an issue.

Wang et al. (2012) conducted research on the capacity of open saline aquifers to store CO_2, employing numerical modeling techniques. The precise estimation of CO_2 storage potential in deep saline aquifers presents a complex challenge. Nonetheless, it is essential to assess whether a proposed storage site possesses adequate capacity for CO_2 sequestration initiatives. In this study, the team focused on evaluating the CO_2

storage capabilities within a simplified reservoir structure, characterized by stratified potential storage layers underpinned by an impermeable cap rock.

Wang et al. (2021) studied the influence of the mechanical properties of low-permeability sandstone reservoirs on the efficacy of CO_2 geological storage. They investigated how injecting CO_2 into deep geological formations affects the reservoir's pore pressure and effective stresses, leading to changes in porosity and permeability sensitive to stress. Such changes have implications for the rate and distribution of CO_2 injection, as well as the overall storage capacity in the chosen reservoir.

Focusing on the Liujiagou reservoir, an early Carbon Geological Storage (CGS) project in the Ordos Basin's saline aquifers in China, the simulations revealed that the mechanical characteristics of the reservoir had a noticeable effect on permeability, the extent of CO_2 migration, injection rates, and the total storage volume, while only slightly altering pore pressure and porosity. It was observed that the mechanical response led to an increase of up to 13.1% in the lateral migration distance of CO_2 at an injection pressure of 5 MPa. Furthermore, over a five-year period of continuous injection, the total CO_2 storage capacity increased by 11.6 %.

Chen et al. (2022) conducted a study on the combined process of CO_2 geological storage and geothermal energy extraction in a semi-enclosed, narrow reservoir. The concept of CO_2 plume geothermal (CPG) production, developed alongside existing or completed CO_2 geological storage projects, presents a novel approach for deriving renewable energy from non-carbon sources and mitigating the expenses associated with CGS.

The above discussed techniques are applied and considered after the CO_2 gas is released into the atmosphere. Al Hameli et al. (2022) studied the CGS method in geological formations by evaluating the matrix of capture mechanism through chemical, physicochemical, and physical methods.

Dalkhaa et al. (2013) explored the dynamics of CO_2 storage within the Devonian Nisku aquifer, known for its H_2S content, situated in the vicinity of Wabamun Lake, Alberta, Canada. This aquifer, part of the Alberta Basin, has been recognized as a potential site for CO_2 sequestration despite its significant H_2S concentrations. Through numerical simulations, the research aimed to understand how the presence of dissolved H_2S in the brine would affect the behavior of injected CO_2. The results indicated that the

presence of H_2S did not lead to major alterations in geochemical reactions when compared to simulations without H_2S. Both scenarios showed considerable dissolution of dolomite, leading to slight increases in the aquifer's porosity and permeability. The study found that a majority of the injected CO_2 remained in the Middle Nisku formation as a free supercritical phase, while a smaller portion dissolved into the brine.

Li et al. (2018) conducted a comprehensive study on the geological characterization and numerical modeling of CO_2 storage within an aquifer formation located offshore of Guangdong Province, China. The Lufeng (LF) 2-1 structure, distinguished as the most prominent anticlinal formation in the Zhu I depression of the Pearl River Mouth Basin. The research involved the development of a 3D model using the TOUGH2/ECO2N tool, which was based on formation parameters derived from an extensive analysis of well and seismic structural data. The numerical outcomes of this study revealed that an increase in CO_2 injection volume does not proportionally increase the CO_2 distribution, indicating nonlinear relationships between these variables. Consequently, the LF2-1 structure emerges as a promising offshore candidate for large-scale industrial CO_2 storage in deep saline aquifers. Furthermore, the insights gained from this study are instrumental in informing site selection processes for offshore CO_2 geological storage projects in the Guangdong Province.

Li et al. (2020) embarked on a numerical investigation into the effects of convective mixing during the geological storage of impure CO_2 in deep saline aquifers. The study highlighted the significance of CO_2 dissolution into formation brine, leading to density-driven convective mixing. This process is crucial for enhancing the transfer rate of free-phase CO_2 into saline aquifers, thereby playing a pivotal role in the efficient and secure long-term geological storage of CO_2. In real-world applications, CO_2 is often co-injected with various impurities to lower capture costs or to simultaneously dispose of hazardous substances such as SO_2 and H_2S. The numerical simulations conducted in this research demonstrated that, in contrast to pure CO_2 scenarios, the addition of SO_2 uniquely intensifies the convective mixing process in the brine. On the other hand, most common impurities tend to delay the onset and reduce the strength of convective mixing. Notably, a single impurity like N_2 can represent the collective effect of all air-derived impurities in forecasting the progression of convective mixing.

The physical characteristics of CO_2 as well as how it transforms into different phases under various pressure and temperature settings must be considered while choosing an acceptable geologic site for CO_2 storage. Although CO_2 can exist in a variety of states (including gas, liquid, solid, and supercritical), the significant increase in pressure and temperature that occurs when it is injected into geological formations at depths greater than 800 meters frequently causes it to take on the form of a supercritical fluid. The effectiveness of CO_2 storage in geological media is measured by the amount of CO_2 stored per unit volume (Bachu, 2003), boosts storage security and gets better as CO_2 density goes up due to a reduction in buoyant force. Geochemical interactions and geological conditions are the main determinants of the change in CO_2 density. For instance, depending on the temperature gradient, the density of CO_2 may drastically increase or decrease with depth (Ennis-King and Paterson, 2001; Kovscek, 2002). It would therefore be preferable to store CO_2 in cool sedimentary basins with little change in temperature (Metz et al., 2005). The contamination caused by CO_2 and methane (CH_4) mixing is another factor that affects CO_2 density. This contamination may reduce density and jeopardize the security of storage, especially in gas reservoirs that have been depleted (Raza et al., 2017). The solubility of CO_2 in water and their interfacial tension are additional key factors that control the storage processes before, during, and after injection. They frequently do; however, both rise with pressure and reduce with a rise in temperature (Metz et al., 2005; Chalbaud et al., 2009; Iglauer, 2011).

2.2. Advancements And Challenges in CCS

Kim et al. (2022) embarked on a detailed study concerning the implementation of oxy-fuel power plants equipped with carbon capture technologies, assessing the resultant effects on energy, economic aspects, and environmental impacts. This pivotal research illuminates the potential of CO_2 storage technologies when integrated with global warming estimation methods to analyze the economic and climatic repercussions of CO_2 storage, across varying sources of CO_2 emissions.

The economic feasibility of geological Carbon Capture and Storage (CCS) is a cornerstone in the implementation and commercialization of Carbon Capture, Utilization, and Storage (CCUS) technologies. Highlighted by Olajire (2010) and Pires et al. (2011), the cost of capturing CO_2 is identified as a critical factor. These costs not

only encompass the capture but also the expenses related to compression—necessary to compensate for the operational pressures, transportation, and storage of CO_2 at varying initial pressures. The research delineates a significant variance in the cost of CO_2 capture, dependent on the source, with averages ranging from $40 to $80 per ton for coal- and gas-fired power plants and $15 to $60 per ton for streams with higher CO_2 levels, such as those from natural gas processing or bioethanol production. For smaller or diluted CO_2 streams, such as those from industrial furnaces, the costs are higher, yet they are capped below $100 per ton.

The financial burden of CCS technologies poses a global challenge, deterring industries and power plants from adopting these technologies due to the high costs of carbon capture equipment and the operational expenses, including maintenance and manpower. A significant hurdle in the realization of CCS technologies is the cost associated with extracting CO_2 from the emissions of fossil fuel-powered plants, emphasizing the urgent need for more cost-effective CO_2 capture methodologies to promote CCS adoption and feasibility.

For the successful implementation of CCUS, financial stability and profitability are essential to attract investments. The current landscape, characterized by a lack of a comprehensive policy, regulatory frameworks, and detailed storage assessments, has weakened the momentum towards CCUS implementation and research.

Mackler et al. (2021) underscore the critical role of government policies in bolstering CCS implementation to significantly mitigate climate change. Insights from various policy implementations across the globe reveal the effectiveness of financial incentives, coupled with compulsory targets and mandates, in driving technology adoption. Support from diverse coalitions, including energy companies, labor unions, researchers, and environmental NGOs, has been vital, although such support is not universally echoed among these groups.

Sustainable Development Goal 13 calls for urgent action against climate change, aligning with the Net Zero Emissions (NZE) target to reduce CO_2 emissions by half by 2030 and achieve net-zero by 2050. Feedback from the Paris Accord and the Intergovernmental Panel on Climate Change (IPCC) suggests that immediate, substantial measures are crucial within the next few decades to address climate risks. Public perception plays a significant role in the adoption of CCS technologies, which,

unlike other climate solutions, include non-renewable applications, highlighting the need for increased public awareness and acceptance.

Environmental risk assessments are critical for understanding the hazards associated with Enhanced Oil Recovery (EOR) methods, which account for about 30 % of global energy production. The selection of appropriate EOR techniques and strategies to mitigate associated risks is crucial, given the potential environmental impacts, including marine pollution and atmospheric emissions. The absence of a unified technological framework addressing drilling discharges, produced water management, and air emissions from EOR techniques in offshore settings points to an urgent need for integrated approaches to comprehensively address the environmental impacts of EOR processes.

3. METHODOLOGY

This research design delineates an investigation into the geochemical effects of CCS technology within the Bell Creek Oil Field, focusing on its impacts on storage capacity, energy consumption, and environmental factors. The primary research question driving this study into the evaluation of CCS technology within the Bell Creek Oil Field is: "What are the implications of geochemical effects during the storage of carbon capture on the storage capacity, energy consumption, and environmental impact within the region?" This inquiry seeks to ascertain the influence of geochemical processes on key parameters such as storage capacity, energy utilization, and environmental outcomes associated with CCS technology implementation, thereby providing a nuanced understanding of the complex interactions shaping the efficacy and sustainability of CCS deployment in the Bell Creek Oil Field (Figure 3.1).

In the initial introduction of the methodology section, the study incorporates a detailed geological characterization of the field, involving analysis of core samples.

The geological assessment aims to delineate the stratigraphy, structure, and petrophysical properties of the reservoir, which are critical for understanding CO_2 storage capacity and containment integrity.

To complement the geological and geochemical analyses, the study employs advanced reservoir simulation techniques. These simulations are integral for predicting CO_2 behavior post-injection, including its migration patterns, the extent of CO_2 plume dispersion, and the potential for mineral trapping. The simulation model is calibrated using historical field data and validated through sensitivity analyses to ensure its reliability in forecasting the outcomes of CCS projects.

Furthermore, the economic evaluation extends beyond mere cost analysis to include an examination of potential revenue streams from enhanced oil recovery (EOR) operations, where applicable, and carbon credits under various regulatory frameworks.

This comprehensive financial model assesses the economic viability of CCS by comparing the net present value (NPV) of the project against traditional and alternative energy projects.

In assessing environmental impacts, the methodology adopts a lifecycle perspective, evaluating not only the direct effects of CO_2 injection but also the indirect impacts on local ecosystems, water resources, and air quality. The environmental analysis also considers the project's contribution to mitigating climate change by quantifying the amount of CO_2 emissions avoided through its implementation.

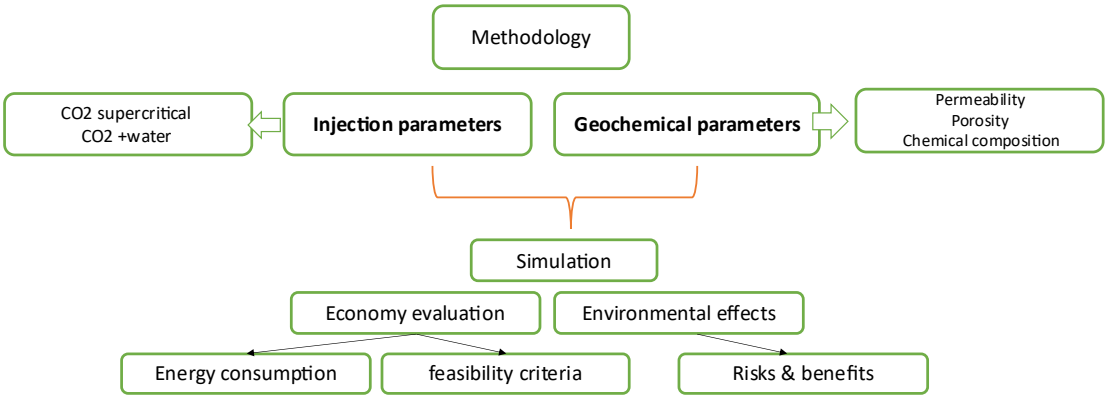

Figure 3.1. A methodological framework for CCS.

The study focuses on geochemical reactions within the well, consequently impacting storage capacity that the chemical interactions between injected carbon dioxide and formation water will engender alterations in the geological properties of the reservoir, thereby affecting its capacity to store carbon, the overall feasibility of CCS deployment in the region, and the energy requirements associated with carbon capture and storage processes. This analysis underlines the significance of understanding the geochemical effects induced by CCS implementation to optimize its operational efficiency and minimize adverse environmental impacts within the region.

The research aims to evaluate the potential of geological site in carbon capturing and sequestration using geological modeling by considering the site characteristics and attributes in context of enhanced oil recovery. It is mainly based on the geological site characteristics evaluation, its modeling and to study the possible potential risks and hazards associated in CCS. The financial models and economical aspect will play a

supportive role in building the argument for the feasibility and potential effectiveness evaluation of geological site storage for CO_2 emissions.

3.1. Study Area

The Powder River Basin, situated in the southeastern region of Montana and the northeastern part of Wyoming, is renowned for its substantial petroleum reserves, notably in the Salt Creek and Bell Creek oil fields (Figure 3.2).

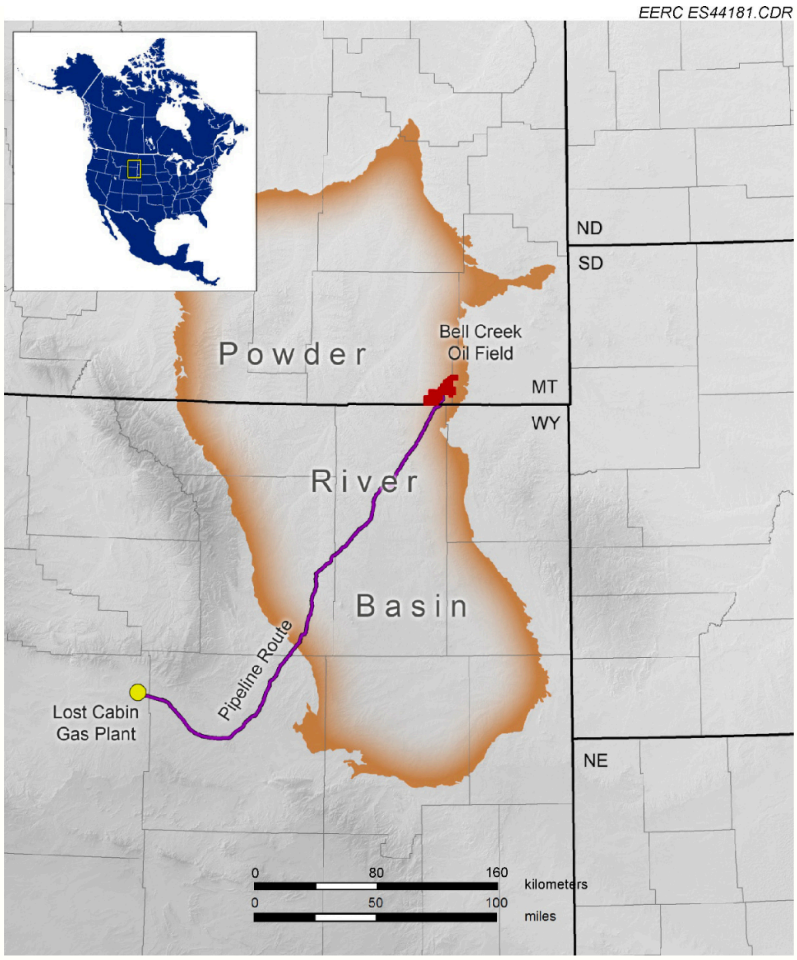

Figure 3.2. Showing the location of Bell Creek oil field (Gorecki et al., 2012).

These oil and gas resources are primarily extracted from geological formations dating from the Pennsylvanian to the Tertiary periods (Figure 3.3). However, the predominant sources are the extensive Lower Cretaceous reservoirs, including the muddy sandstone formations (Dolton et al., 1990). A significant contributor to the hydrocarbon supply in these Lower Cretaceous reservoirs is the Mowry Shale (Anna

and Cook, 2008). Additionally, the Lower Cretaceous Skull Creek Shale and Fuson Shale have been identified as minor sources of hydrocarbons (Anna, 2009).

These reservoirs are primarily composed of marine and nonmarine sandstone, siltstone, and mudstone, deposited across diverse sedimentary settings. A significant portion of the Muddy's output is linked to incised valley systems located within stratigraphic traps (Dolson et al., 1991). By synthesizing numerous smaller studies, a holistic perspective on the reservoir's heterogeneities and the intricate depositional system of the basin has been developed (Waring, 1975; Weimer et al., 1982; Gustason, 1988; Martinsen, 1994; Donovan, 1995; Anna and Cook, 2008; Toner 2019). The following sections will provide a detailed overview of Bell Creek's significance in terms of CO_2 sequestration, a description of its reservoir characteristics, and an explanation as to why it is ideally suited for CCS implementation.

3.2. Geology Of the Bell Creek Site

The Bell Creek site, positioned at the northeastern frontier of the Powder River Basin, is distinguished by its significant hydrocarbon reserves under high pressure (Figure 3.3). This locale has observed a decline in oil production, prompting the adoption of CO_2 injection strategies aimed at boosting oil recovery and facilitating CO_2 sequestration. This technique has revitalized the field, which boasts a substantial production milestone of 133.4 million barrels, representing a significant portion of its potential. The process involves transporting an estimated 1,416,000 cubic meters of CO_2 from a nearby gas processing facility in Fremont County for separation and injection (Sharaf and Sheikha, 2021). This initiative not only addresses the immediate challenges of declining oil yields but also contributes to broader environmental goals by sequestering CO_2, thereby reducing greenhouse gas emissions.

The Bell Creek is formed in the Early Cretaceous period, marked by the expansion of the Western Interior Seaway and the formation of the Dakota Formation, signaling a shift from terrestrial to marine sedimentation. This transition was further emphasized during the Albian Age with the deposition of Skull Creek shale, extending the geological narrative and enhancing the site's stratigraphic complexity. These geological formations, rich in historical and sedimentological significance, underpin the area's hydrocarbon potential and inform the strategic implementation of CO_2 injection for enhanced oil recovery. This multidimensional approach not only

underscores the technical and environmental feasibility of such interventions but also highlights the critical role of geological understanding in optimizing resource extraction and environmental conservation efforts.

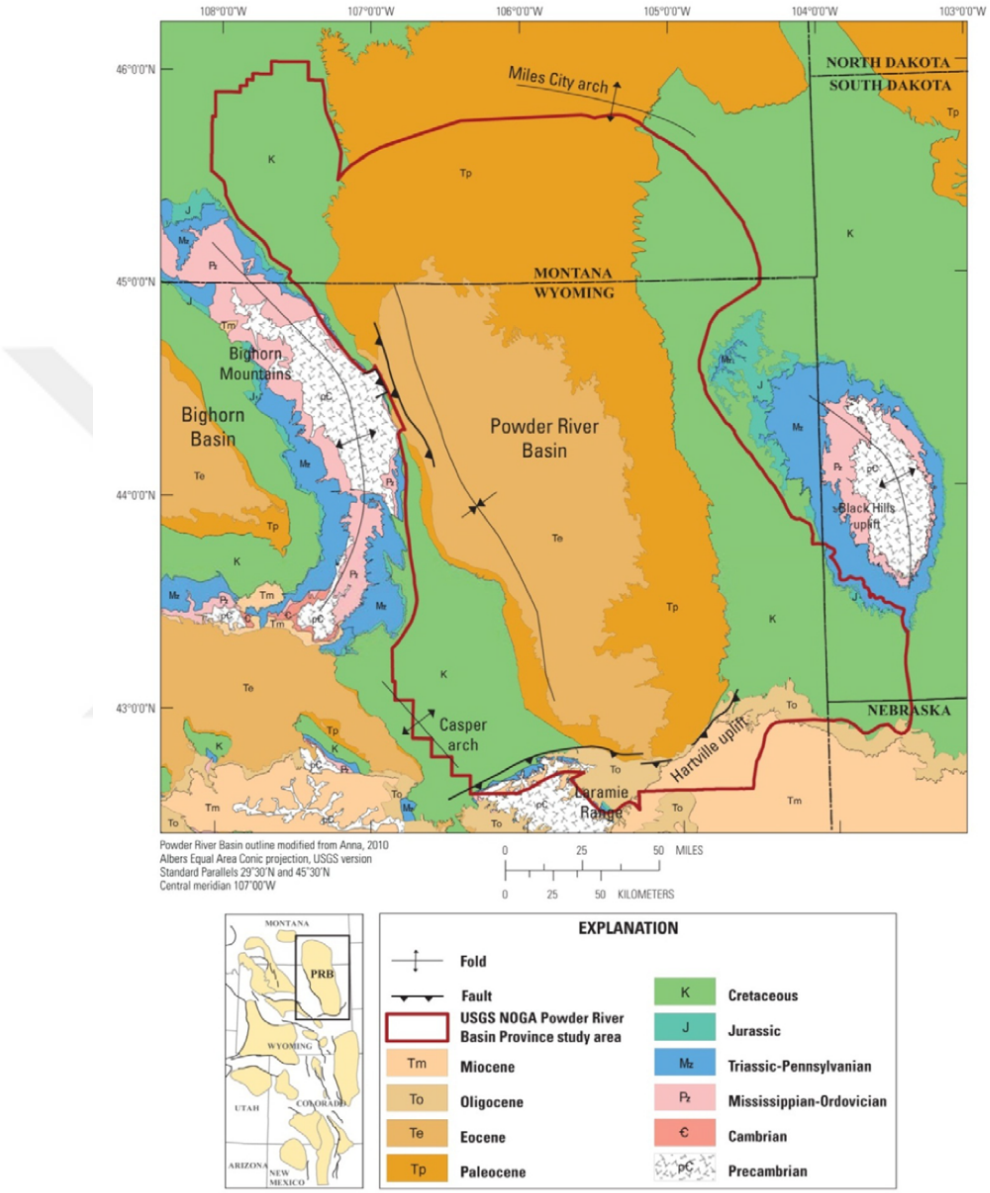

Figure 3.3. Geologic map of the Powder River Basin study area encompassing Wyoming, Montana, South Dakota, and Nebraska (Stoeser et al., 2007; Anna, 2010).

During the mid-Albian period, the Skull Creek experienced subaerial exposure due to northward regression, leading to the formation of significant deltas and major drainage systems that deeply incised into the Skull Creek Shale, indicative of the lower Muddy Sandstone (Wulf, 1962). In the Bell Creek Field, the Muddy Formation is

characterized by a stratigraphic trap, with up-dip sand facies gradually transitioning into shale facies towards the east, indicative of the ancient shoreline (Figure 3.4). This formation reflects a dynamic interplay between marine transgressions and regressions, facilitating the deposition of diverse sedimentary facies (Gorecki et al., 2012).

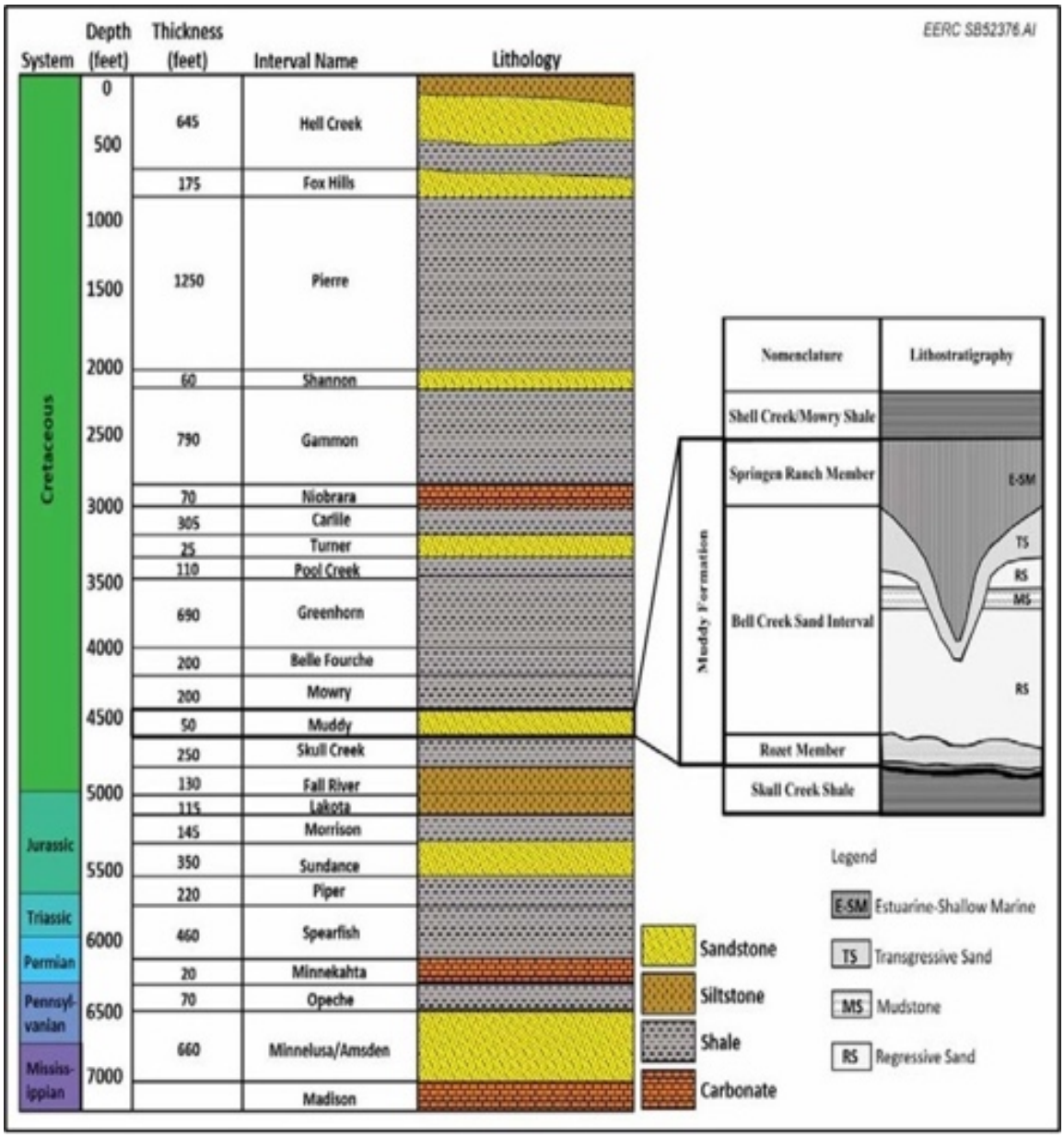

Figure 3.4. Local stratigraphy of the Bell Creek development area (Sharaf and Sheikha, 2021).

The Bell Creek Field is identified by its sandstone reservoir, encompassing the Muddy formation from the Lower Cretaceous period at depths between 1310 and 1372 meters. Its sedimentological characteristics are predominantly composed of sandstone and

shale, closely related to the Powder River Basin. The genesis of organic substances within the Bell Creek Field is attributed to geological traps within the Lower Cretaceous Muddy formation sandstones (Figure 3.5). The primary barrier against fluid leakage towards the surface or into overlaying aquifers is provided by the Mowry Formation's Upper Cretaceous shale. Situated above this formation are multiple layers of shale with low permeability, such as the Belle Fourche, Greenhorn, Niobrara, and Pierre shales. These formations act as additional safeguards, offering extra layers of security to prevent the upward migration of fluids across the field in the rare event that the main seal is compromised (Rawn-Schatzinger, 1993).

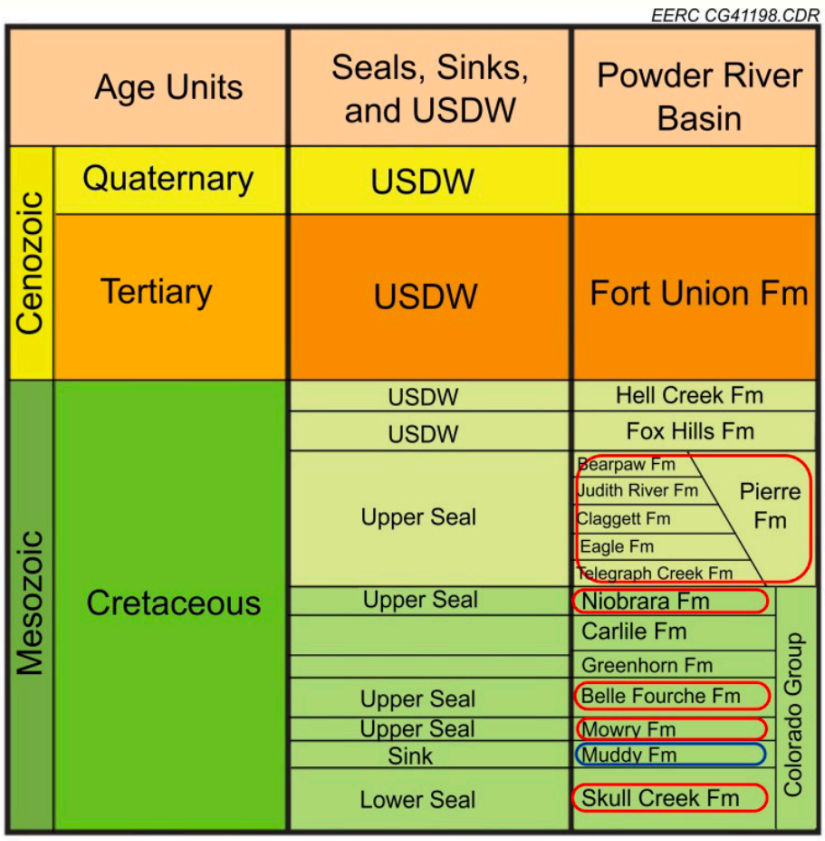

Figure 3.5. Stratigraphic column of the Powder River Basin, Montana. Sealing formations are circled in red, and the primary sink formations are circled in blue. (Gorecki et al., 2012).

The evaluation and studies of Bell Creek Enhanced Oil Recovery with CO_2 injection and storage is a valuable source to build a strong, cost-effective validation process on a larger scale, storing capacity of a fully developed geological site for oil generation and its enhancement through CO_2 injection. The findings of the target site are valuable

in the context of CO_2 injection at an upper scale on sinking potential, regulating methods, and implementation of a successful approach for CO_2 storage using enhanced oil recovery strategy. The validation and evaluation process will be furnished and refined with each step taken from initial planning to final injection, including all the processes involved via post-closure (Hamling, 2013).

3.3. Data

The study involved an extensive analysis of core data and geochemical assays from the 33-14R well, conducted by the Energy and Environmental Research Center, University of North Dakota (2018). Core samples were collected at various depths, with their physical properties meticulously measured, including bulk volume, grain volume, grain density, pore volume, and porosity (Energy and Environmental Research Center (2018). Additionally, geochemical characterization was performed, detailing the weight percent of major oxides and elements, providing a window into the mineralogical composition of the subsurface formations at different stratigraphic levels.

The research will be supported by the geological characteristics evaluated and studied previously through simulation and modeling. The site characteristics will help in finding the gaps as well as properties which are favorable in capturing and injecting the CO_2 into Bell Creek oil field wells. The EOR for oil production and CO_2 capturing potential of Bell Creek Oil Field will be the main area of research and its link to potential attributes of sites in context of impacts, hazards, risks and financial strategies.

Secondary data acquisition through literature review and analysis of industry reports. The study's variables encompass the implementation of CCS technology and associated geochemical processes as independent factors, while storage capacity, energy consumption, and environmental impact serve as dependent variables.

Limitations such as data collection constraints and potential biases are acknowledged, with a proposed timeline and budget facilitating the research's execution. Upon

completion, this study aims to provide a comprehensive understanding of the evaluated phenomena, paving the way for future research endeavors in the field.

3.4. Physical Properties and Geochemistry Data Of The Region

The geochemical assessment of sediment samples procured from varying depths at Bell Creek Oil Field offers a robust foundation for evaluating the geochemical interactions during CO_2 storage. Table 3.1 presents an array of minerals that have been identified within both the Muddy and adjacent geological formations (Glazewski et al., 2013).

Table 3.1. Minerals in the Muddy and adjacent formations

Mineral Phase	Formula
Albite	$NaAlSi_3O_8$
Anorthite	$CaAl_2Si_2O_8$
Apatite	$Ca_{10}(PO_4)_6(OH,F,Cl)_2$
Calcite	$CaCO_3$
Chlorite	$(Mg,Fe)_3(Si,Al)_4O_{10}$-$(OH)_2$•$(Mg, Fe)_3(OH)_6$
Illite	$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}([OH]_2,[H_2O])$
Kaolinite	$Al_2Si_2O_5(OH)_4$
Microcline	$KAlSi_3O_8$
Monazite	$(Ce,La)PO_4$
Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$
Orthoclase	$KAlSi_3O_8$
Pyrite	FeS_2
Quartz	SiO_2
Rutile	TiO_2
Siderite	$FeCO_3$
Zircon	$ZrSiO_4$

The table meticulously lists each mineral's phase, coupled with its corresponding chemical formula. This includes common minerals such as Quartz (SiO_2) and Calcite ($CaCO_3$), as well as less prevalent minerals like Monazite ((Ce, La) PO_4) and Rutile (TiO_2). The range of minerals captured here is indicative of the complex geochemical processes that have influenced the formation and evolution of these geological structures. The inclusion of major, minor, and trace minerals provides a

comprehensive overview of the mineralogical composition that characterizes the Muddy and its neighboring formations.

Table 3.2 encapsulates the core laboratory physical property data derived from the 33-14R well in the Bell Creek Oil Field, delineating critical attributes such as sample depth, bulk volume, grain volume, grain density, pore volume, and measured porosity for each core sample identified by EERC STAR numbers and Core Labs Sample numbers (Glazewski et al., 2013).

Table 3.2. Physical properties of core data in Bell Creek Oil Field

EERC STAR	Core Labs Sample	Depth (ft)	Scanned Bulk Volume (cm^3)	Measured Grain Volume (cm^3)	Measured Grain Density (g/cm^3)	Measured Pore Volume (cm^3)	Measured Porosity (%)
118018	1 PPB	4453,5	24,4	19,1	2,68	5,28	21,7
118019	2 PPB	4453,75	20,2	16,1	2,68	4,06	20,1
118020	3 PPB	4454	23,2	18,5	2,67	4,71	20,2
118021	4 PPB	4454,35	22,4	17,2	2,67	5,18	23,2
118023	5 PPB	4455,1	22,6	17,0	2,68	5,54	24,5
118024	6 PPB	4455,75	21	15,4	2,68	5,65	26,9
118025	7 PPB	4457,55	22,8	20,1	2,68	2,66	11,7
118033	8 PPB	4470,3	22,8	20,8	2,65	2,00	8,78
118034	9 PPB	4470,65	23,1	22,0	2,54	1,1	4,75

The data spans depths from 4453.5 feet to 4470.65 feet, revealing notable variations in physical properties of the subsurface materials. Bulk volume measurements range from 20.2 cm^3 to 24.4 cm^3, while grain volumes vary between 15.4 cm^3 and 22.0 cm^3, reflecting the differences in the rock matrix constitution. Grain densities are consistently high across samples, predominantly around 2.68 g/cm^3, indicating the mineralogical consistency of the sampled formations. Pore volumes and measured porosities exhibit significant variability, with porosity values ranging from as low as 4.75% to as high as 26.9%, highlighting the heterogeneity in the reservoir's pore space distribution.

Table 3.3 presents a comprehensive geochemical analysis of rock samples extracted from the 33-14R well in the Bell Creek Oil Field, focusing on the weight percent of

major oxides and elements at various depths measured in feet. The analyzed components include Silicon Dioxide (SiO_2), Aluminum Oxide (Al_2O_3), Iron (III) Oxide (Fe_2O_3), Titanium Dioxide (TiO_2), Phosphorus Pentoxide (P_2O_5), Calcium Oxide (CaO), Magnesium Oxide (MgO), Sodium Oxide (Na_2O), Potassium Oxide (K_2O), Sulfur Trioxide (SO_3), Barium Oxide (BaO), Chlorine (Cl), Manganese(II) Oxide (MnO), Strontium Oxide (SrO), across depths ranging from 4425.50 feet to 4470.65 feet. The data illustrates the variation in geochemical composition with depth, highlighting significant fluctuations in the concentration of specific elements and oxides, which may indicate changes in geological formations, depositional environments, or diagenetic processes.

Table 3.3. Geochemical composition of rock samples in Bell Creek Oil Field

Depth, ft	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O (%)	SO_3 (%)	Unknown (%)
4425,5	78,15	10,86	3,66	1,03	1,25	1,38	1,31	0,38	1,31
4426,3	78,54	11,57	3,4	0,66	1,23	1,47	1,32	0,32	0,87
4426,4	79,27	11,59	3,33	0,62	1,21	1,47	1,3	0,3	0,27
4429,1	71,62	13,6	6,53	0,88	1,41	1,53	1,67	0,23	1,72
4430,2	76,54	12,36	3,56	0,67	1,32	1,51	1,46	0,23	1,65
4433,1	73,74	13,15	4,52	0,69	1,4	1,58	1,65	0,23	2,38
4434,4	74,16	13,51	4,2	0,63	1,28	1,35	1,71	0,24	1,79
4437,8	75,05	13,05	4,12	0,63	1,29	1,39	1,74	0,24	1,5
4445,3	74,76	12,86	4,04	0,61	1,29	1,4	1,68	0,25	2,34
4453,5	93,27	1,94	1,68	0,49	0,11	0,22	0,4	0,74	0,78
4453,75	90,1	3,56	1,18	1,63	0,23	0,35	0,75	0,28	1,53
4454	89,1	2,48	1,08	2,03	0,18	0,27	0,59	0,58	2,95
4454,35	84,97	4,31	1,8	2,13	0,35	0,41	0,81	0,65	3,95
4455,1	91,62	3,13	0,92	0,26	0,19	0,35	0,81	0,33	1,66
4455,75	91,2	1,38	3,18	0,21	0,09	0,27	0,4	1,95	0,79
4457,55	72,38	7,48	2,15	9	0,64	0,47	1,45	0,37	5,34
4470,3	66,68	14,29	3,84	6,29	0,79	0,89	3,49	0,26	2,73
4470,65	56,22	11,53	3,15	14,48	0,5	0,59	3,63	0,24	8,9

3.5. The Suitability of Bell Creek Oil Field for CCS

The Bell Creek Reservoir shows high porosity and permeability for CO_2 injection. The effective porosity of the site is 25%-35%. The reservoir has high permeability ranging from 100 millidarcies to 1175 millidarcies (Table 3.4). The results of the study by Haddenhorst (1968) show that the oil and gas fields in the PCOR Partnership region, i.e., Bell Creek, have a storage capacity of over 3.5 billion tons of CO_2.

Table 3.4. General Specification of Bell Creek Oil Field

Discovery Date	June 6, 1967
Location	NE Sec. 33, T8S, R54E
Initial Production	230 Barrels Oil Per Day (BOPD)
Development Pattern	40.acre
Number Of Producing Wells (6-1-68)	277
Field MER Rate	300 Barrels Oil Per Day (BOPD)/Well
Cumulative Production (6-1-68)	7,188,066 bbl of Oil
Lower Cretaceous Paleogeographic	~130-140 Ma
Porosity	27.0 %
Permeability	1,700 md
Interstitial Water (Est.)	20 %
Average Net Pay	24 ft (7.315 Meters)
Average Depth	4,425 Feet (1348.74 Meters)
Reservoir Pressure At 800 Ft	1,180 psi
Crude Oil Gravity	32 to 40 API
Initial Gas in Solution	213 cu ft/bbl
Saturation Pressure	1,180 psi
Viscosity At Reservoir Conditions	2.82 cp
Reservoir Temperature	110 F (43.33 ºC)
Formation Volume Factor	1.112

Within the study area, the quality and thickness of the reservoir differ across each geological unit. The BC-20 stands out as the segment with the greatest thickness and highest quality of the reservoir. While the sandstone layer in certain wells can extend up to 35 feet, it typically does not exceed 20 feet (Figure 3.5). Conversely, the shale layers are comparatively thinner, often measuring a few feet or less. However,

production data suggest that these shale beds act as horizontal barriers, impeding the flow of fluids (Sharaf and Sheikha, 2021).

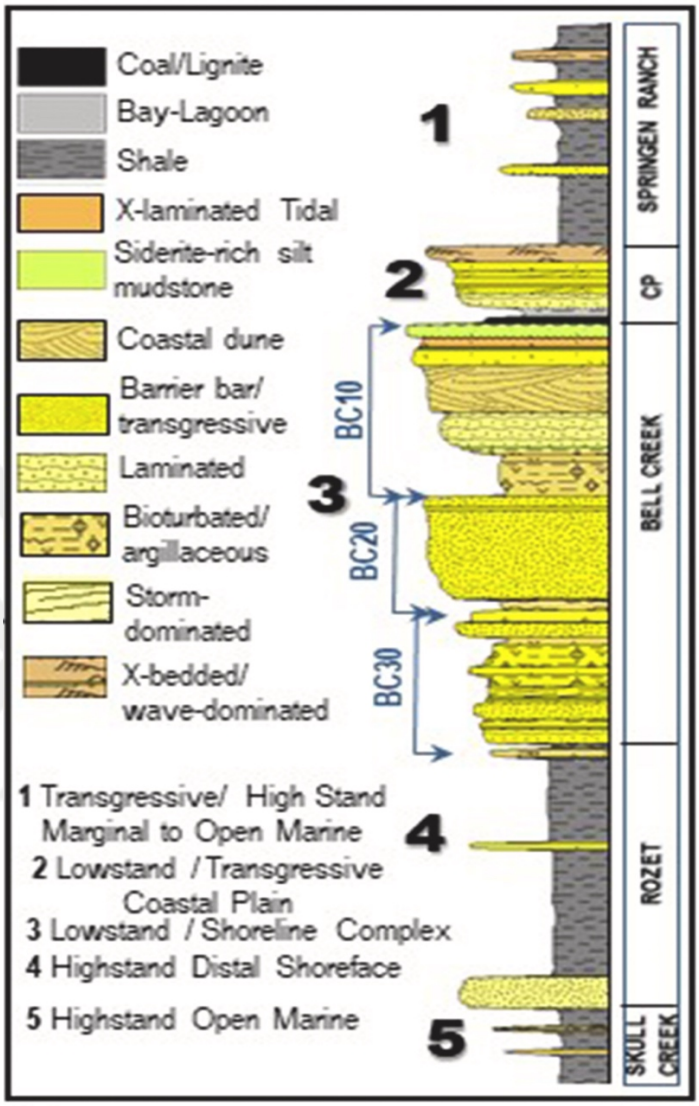

Figure 3.2. Stratigraphic and Sedimentology of Bell Creek Oil Field (Sharaf and Sheikha, 2021).

In the regional context, the hydrostatic pressure, measured at 14.5 MPa at a depth of 1372 meters (21 psi at 1371.6 meters), surpasses the reservoir pressure of the Muddy Formation in Bell Creek, estimated to be around 8.27 MPa (1200 psi). Research indicates that the Bell Creek oil field operates as a hydrodynamically self-contained system, boasting robust reservoir seals that have effectively maintained significant hydrocarbon deposits over extensive geological periods. This finding implies that in the absence of fractures in the reservoir, it should provide a secure and efficient

containment for CO_2 injection (Table 3.4). Moreover, there seems to be a minimal threat to the integrity of the reservoir and its seals during the process of CO_2 injection (Sharaf and Sheikha, 2021).

3.6. Modeling Strategy

In this study, it is conducted a comprehensive modeling strategy to assess the energy consumption, risks, environmental impacts, and geochemical alterations associated with Carbon Capture and Storage (CCS) processes in the Bell Creek Oil Field. The simulation modeling offers guidance in two key areas of decision-making: (1) creating balance in the developmental field plans and (2) aiding decision-making related to operations and investments in the reservoir project.

Leveraging MATLAB, specifically the high-performance technical computing language MATLAB R2021a, we integrate computation, visualization, and programming in an easy-to-use environment. This version is equipped with a wide array of toolboxes for numerical analysis, optimization, and statistics to meet our complex modeling needs. The software's capabilities are further enhanced by Simulink for model-based design and the Parallel Computing Toolbox for efficiently handling large computational tasks. These features were pivotal in developing and calibrating intricate models to simulate the energy requirements across various stages of the CCS process, from CO_2 capture to injection and storage. Leveraging advanced visualization tools for comprehensive analysis, these models are calibrated using data from literature and experimental studies to ensure accuracy and reliability. Additionally, MATLAB is utilized to construct risk assessment models, considering factors such as geological properties and injection parameters, to evaluate potential hazards like CO_2 leakage and induced seismicity. Furthermore, environmental impact models are developed to analyze the effects of CCS operations on the surrounding ecosystem, incorporating field data to validate and refine the simulations. Concurrently, the geochemical alterations during CO_2 storage are examined using HSC Chemistry software, enabling detailed calculations and modeling of CO_2-rock interactions. These findings collectively contribute to a holistic understanding of the CCS process dynamics in the Bell Creek Oil Field, providing valuable insights for informing future CCS deployment strategies and sustainable energy management practices.

Generally, observing and understanding the dynamic fluid behavior within the reservoir site, studying the process, and predicting all factors affecting fluid movement and behavior are challenging. The development of the reservoir and its response over time to various changes and displacements is considered highly uncertain. Simulation enables us to study the quantitative and qualitative parameters of the reservoir to predict the behavior, including fluid dynamics, thereby reducing uncertainties in reservoir characterization.

4. RESULTS AND DISCUSSION

This chapter presents a comprehensive analysis of the geological, environmental, and energy consumption investigations conducted in the context of Carbon Capture and Storage (CCS) within the Bell Creek Oil Field. This chapter delves into the intricate details of the effects of geochemical alteration during the storage of carbon dioxide, elucidating its ramifications on key geological parameters such as porosity, permeability, and leakage potential. Through meticulous examination, the chapter explores how geochemical processes influence the structural integrity of the storage reservoir, consequently shaping its capacity for carbon storage and susceptibility to environmental impact. Furthermore, this chapter critically evaluates the associated energy consumption patterns, elucidating the interplay between technological requirements and operational efficiency in CCS deployment. By findings from geological, environmental, and energy consumption analyses, this chapter offers valuable insights into the multifaceted implications of geochemical alteration on CCS feasibility and sustainability within the Bell Creek Oil Field.

The suitability of the Bell Creek oil field for carbon capture and storage (CCS) can be evaluated using the energy consumption, risks and environmental impacts. According to secondary data and the depth of the storage reservoir, the pressure and temperature conditions in the field are expected to satisfy the conversion of injected CO_2 gas into a supercritical state. This is crucial for safe and efficient CCS, as supercritical CO_2 is denser than gas and less mobile, reducing the risk of leakage. The marked section the Figure 4.1 is shows the practical condition for CO_2 at studied wells. This graph shows the minimum pressure which need to stabilize the CO_2 supercritical phase is higher than approximately 10 Mpa and the temperature up to 30 °C.

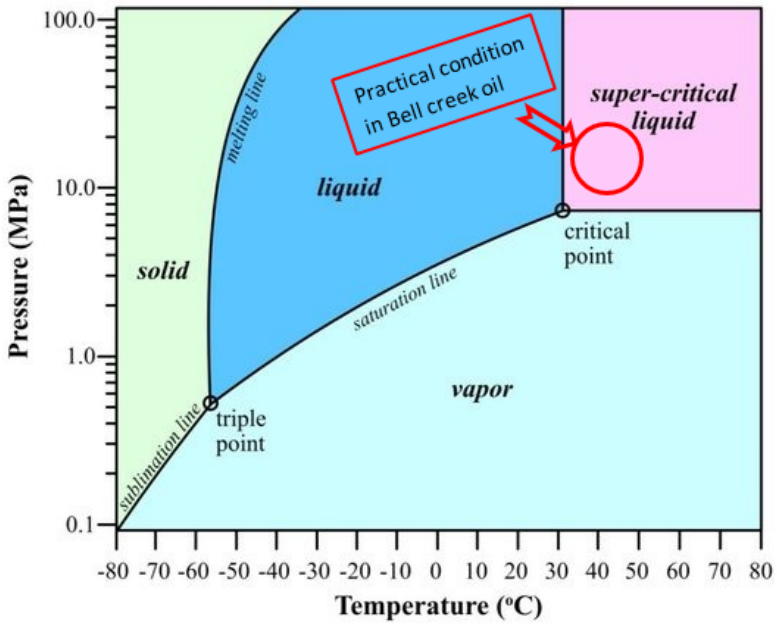

Figure 4.1. Phase stability diagram of CO2 (Glazewski et al., 2013).

4.1. The Effect of CO_2 Long-Term Storage Due to Geochemical Alteration

In the process of injecting carbon dioxide (CO_2) into a well containing brine, it is observed that complete mixing between these two substances does not occur due to their limited solubility. Consequently, distinct phases are formed within the reservoir, comprising CO_2 gas and brine water. The introduction of a low-viscosity fluid, such as CO_2, into the pore spaces of rock saturated with a more viscous fluid, namely brine, engenders an inherently uneven flow pattern as opposed to a uniform one. This phenomenon is termed channeling, characterized by the development of a complex and intricate network resembling branching fingers of CO_2 penetrating the surrounding brine at various magnitudes. The resulting channeling effect significantly influences fluid flow dynamics within the reservoir, impacting the distribution and migration of injected CO_2 and altering the porosity and permeability characteristics of the geological formation. Such observations underscore the complexity of multiphase flow behavior in CCS operations and highlight the importance of understanding and mitigating channeling phenomena to optimize storage efficiency and mitigate potential environmental risks.

In Table 3.1 and Table 3.3 of Chapter 3 are presented the mineral composition of the muddy samples which are tested and reported by National Energy Technology Laboratory. When storing CO_2 underground, it can dissolve slightly in water and salty

brine, even under high pressure and temperature. This small amount of dissolved CO_2 turns the brine into a weak carbonic acid solution, making it acidic (around pH 3). This reaction can be written as:

$$CO_2 + H_2O = H^+ (aq) + HCO_3\text{-} (aq) \quad (4.1)$$

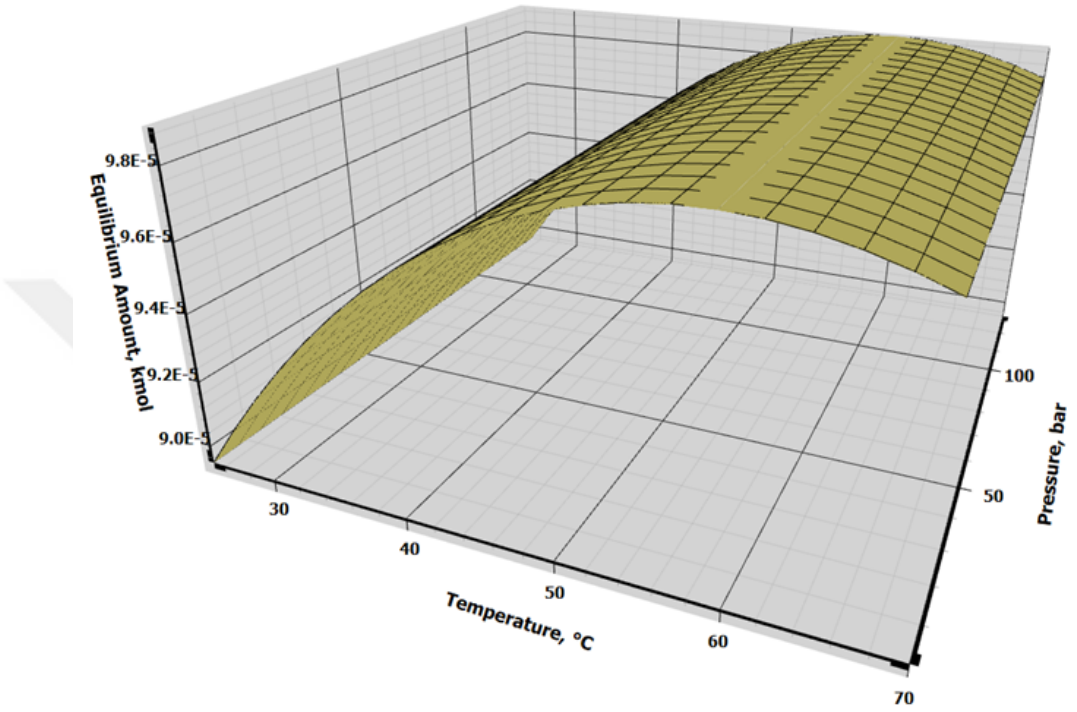

Figure 4.2. Temperature and pressure dependence of HCO3- formation according to reaction 4.1.

This acidic brine can then react with and dissolve silicate minerals like $CaAl_2Si_2O_8$ which is in the region minerals composition (Table 3.1). These reactions neutralize the acidity, according to below reaction.

$$H^+ (aq) + CaAl_2Si_2O_8 + H_2O = Ca^{2+} (aq) + Al_2Si_2O_5(OH)_4 \quad (4.2)$$

Calcium carbonate ($CaCO_3$) in the rock can also neutralize some of the acidity and increase the pH through another reaction:

$$H^+ (aq) + CaCO_3 = Ca^{2+} (aq) + HCO_3^- (aq) \quad (4.3)$$

According to the Table 3.3, a major part of the minerals at sandstone region is Quartz (approximately 78%) which makes Bell creek oil filed suitable for CCS and EOR. But there is also enough $CaCO_3$ in that region which can gradually increase the brine's pH to around 4.6-5. As soon as this acidity level is reached, the neutralization process slows down sharply.

Dissolved CO_2 can also be permanently stored by reacting with released Ca^{2+}, Mg^{2+}, and Fe^{2+}, combine with bicarbonate (HCO3-) to form solid carbonate minerals, primarily calcium carbonate ($CaCO_3$). This process can be summarized by the following chemical reaction:

$$Ca^{2+}\ (aq) + HCO_3^{-}\ (aq) = CaCO_3\ (solid) + H^{+}\ (aq) \qquad (4.4)$$

Moreover, according to sandstone analysis $CaAl_2Si_2O_4$ is presented in that region. So according to below reaction it will react with injected CO_2 and water.

$$CO_2 + CaAl_2Si_2O_4 + 2H_2O = Al_2Si_2O_5(OH)_4 + CaCO_3 \qquad (4.5)$$

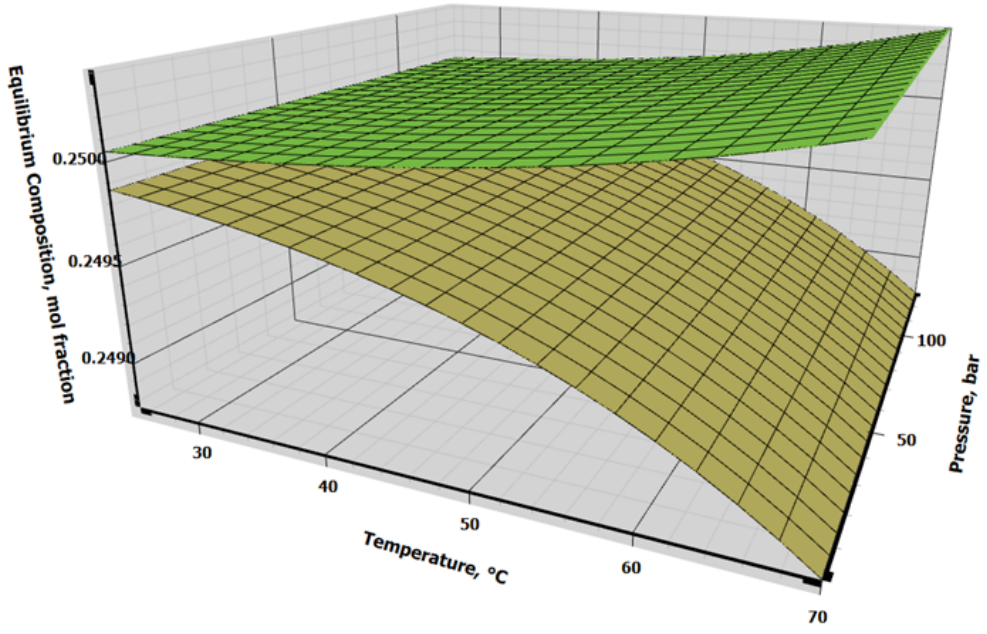

Figure 4.3. Kaolinite and CaCO3 Production from Alumino-Silicate Reaction

The above reaction shows that one molecule of an anorthite is transformed into two different minerals (kaolinite and calcite). Importantly, it also demonstrates the

removal of one CO_2 molecule from the injected CO_2 and its conversion into stable calcite, which gets deposited in the tiny spaces within the surrounding sandstone rock. However, this calcite precipitation only happens at significant speeds when the environment becomes more alkaline (pH around 8), which occurs naturally over time as enough silicate minerals dissolve.

Water infused with CO_2 becomes acidic, typically exhibiting a pH range of 3–5, contingent upon factors like CO_2 partial pressure, water composition, and system temperature. This acidic state facilitates the dissolution of silicate minerals like pyroxene, prevalent in basalt and peridotite.

$$2H^+ + H_2O + (Ca,Mg,Fe)SiO_3 = Ca^{2+}, Mg^{2+}, Fe^{2+} + H_4SiO_4 \quad (4.6)$$

These types of reaction which is happened in the reservoir can promote the mineralization of sediments by decreasing the amount of the acidic water and also by increasing the rate of the precipitation of carbonate minerals when the pH is increased.

According to the formation of ionic species generated during the CO_2 storage in the reservoir in the most important parameters control the geochemical alteration in the mineral is pressure, temperature, pH and partial pressure of CO_2 as well as the water content. Therefore, it is important to investigate the Eh-pH (Pourbiax) diagram of the elements which are existed in the adjacent area. The figures 4.4 to 4.7 show the Eh-pH diagram for Ca, Na, Mg, Fe which are available in that region. SiO_2, TiO_2 and Al_2O_3 reaction in that condition is very slow so we assume that these compounds will not affect the canonization process. As mentioned, before it is obvious the Ca^{+2} and Na^+ will be in the ionic form which can be react with other compound to form new species. But Iron and manganese will react with carbonic acid and will form iron carbonate $FeCO_3$ and manganese carbonate ($MgCO_3$). The diagram is calculated in the real condition (temperature 43.3°C and pressure of 130bar).

The Figure 4.4 shows the stability field for sodium hydride (NaH) at low pH values, indicating it is the most stable species in highly acidic conditions. As the pH increases, there is a transition to the stability of sodium metal (Na(aq)), which is stable in moderately acidic to neutral conditions. Further increase in pH leads to the predominance of sodium bicarbonate ($NaHCO_3$), which is typical in slightly alkaline conditions. In highly alkaline conditions, the diagram shows the stability fields for

sodium carbonate hydrate ($Na_2CO_3 \cdot xH_2O$) and sodium nitrite ($NaNO_2$). The fields are delineated by lines that indicate the pH values at which one species becomes more stable than another. The dashed line marked as a) likely represents a specific activity of a component within the system, which would be a constant under certain conditions. The colors are probably used for visual clarity to distinguish between different stability fields.

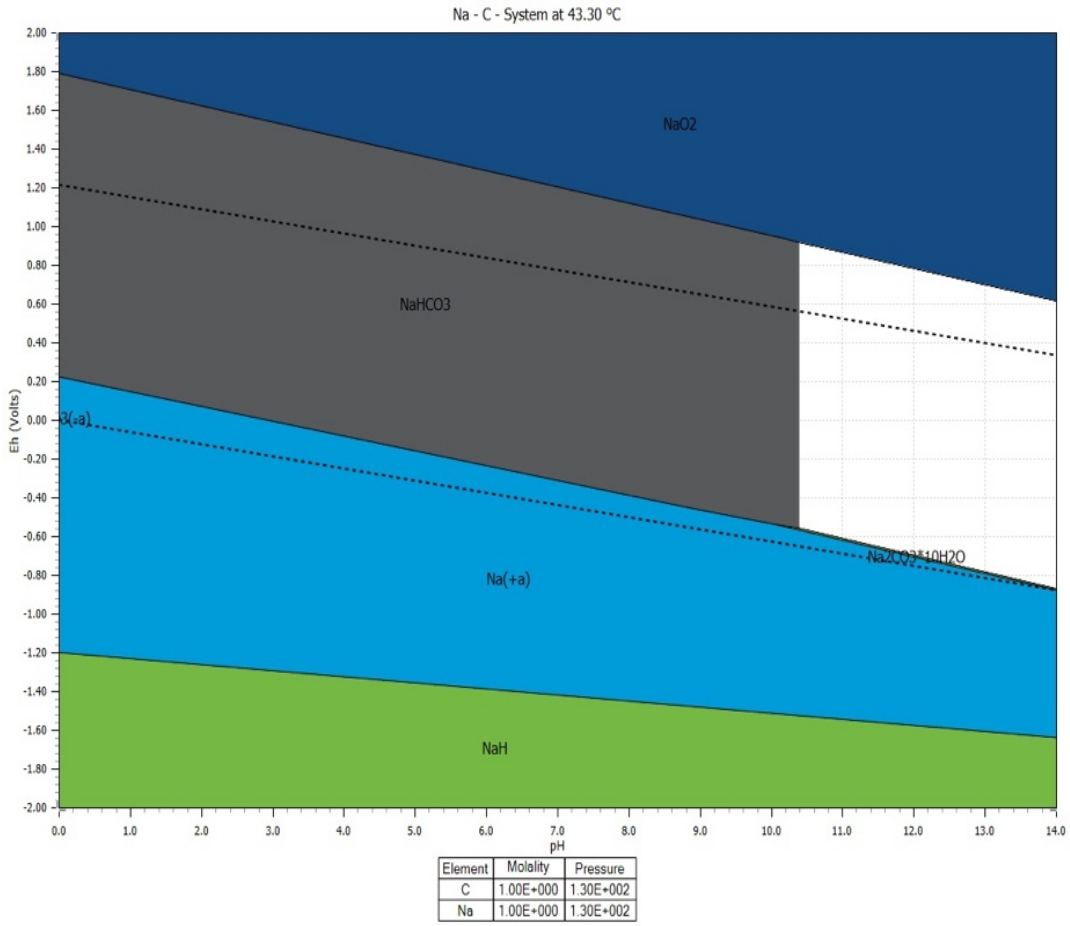

Figure 4.4. Eh-pH diagram of C-Na at temperature of 43.3 °C and pressure of 130 bar.

The Figure 4.5 shows the calcium hydride (CaH_2) is the stable species in pH lower that 2.8, which transitions to aqueous calcium ions (Ca^{2+}(aq)) as the pH increases, indicating that Ca^{2+} is stable over a wide pH range from acidic to just below neutral. As the pH becomes slightly alkaline, the stable species transitions to calcium bicarbonate Ca $(HCO_3)_2$, and further increase in pH leads to the stability of calcium

carbonate ($CaCO_3$). In highly alkaline conditions, calcium hydroxide Ca $(OH)_2$ becomes the stable species.

The dashed line likely represents an iso-activity line for a particular species, which remains constant under the given conditions. It serves as a reference point for comparing the relative stability of the species at different pH levels.

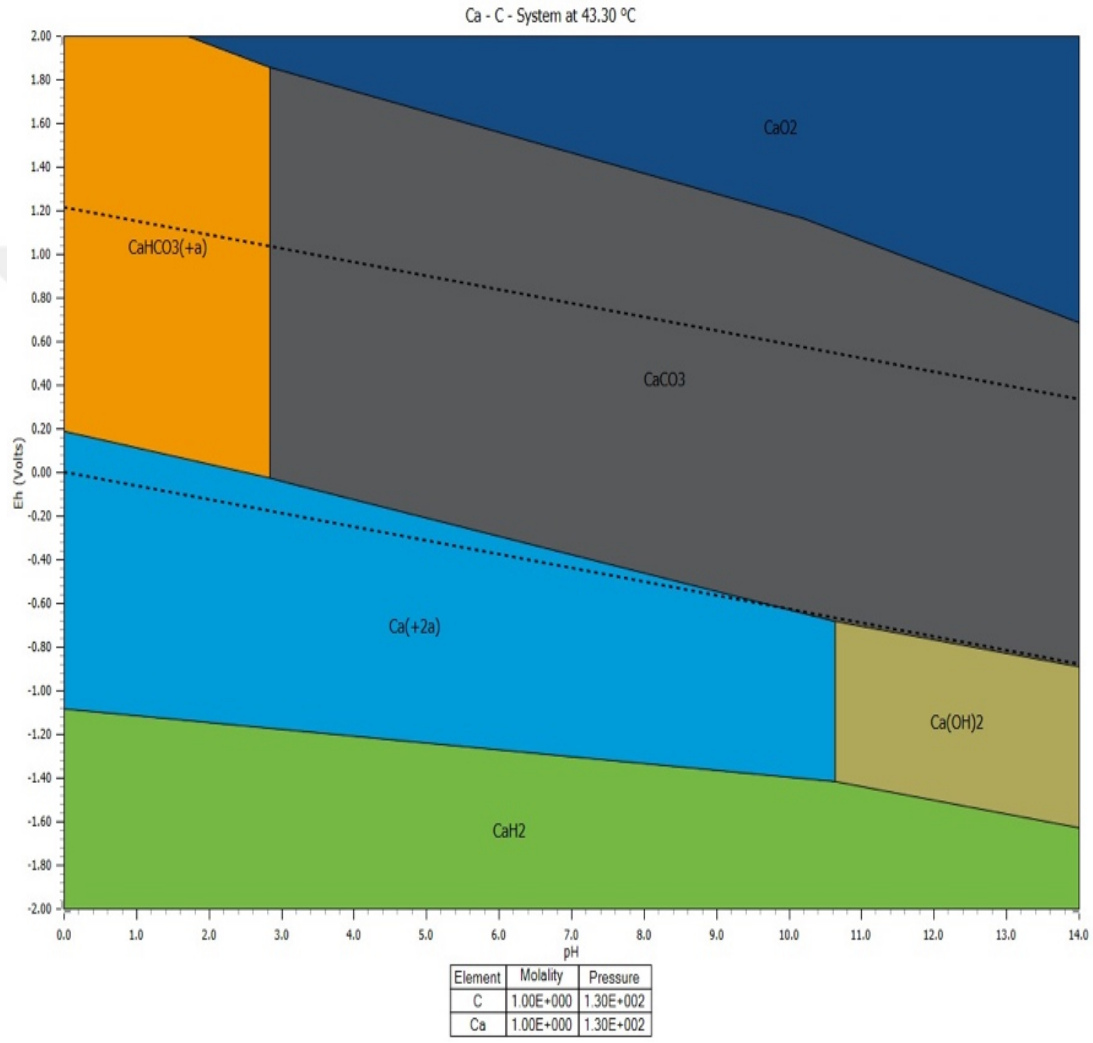

Figure 4.5. Eh-pH diagram of C-Ca at temperature of 43.3 °C and pressure of 130 bar.

As it shows in Figure 4.6, at lower pH values, the stability field for pentadecane ($C_{15}H_{32}$) is shown, indicating its predominance in highly acidic environments. As the pH increases, the system transitions to the stability fields of myristic acid ($C_{14}H_{28}O_2$) and then to a mix of acetic acid (CH_3COOH) and formic acid (CH_2O_2) in moderately acidic to near-neutral conditions.

Moving further towards alkaline conditions, the stability field for ferrous bicarbonate is indicated, which then transitions to ferrous carbonate ($FeCO_3$) in slightly alkaline conditions. As the pH becomes more alkaline, the stable species become bicarbonate HCO_3- and carbonate ions (CO_3^{2-}), which are common carbon species in natural water systems. These carbon species can complex with metal ions, including iron, affecting their solubility and transport in the sediment.

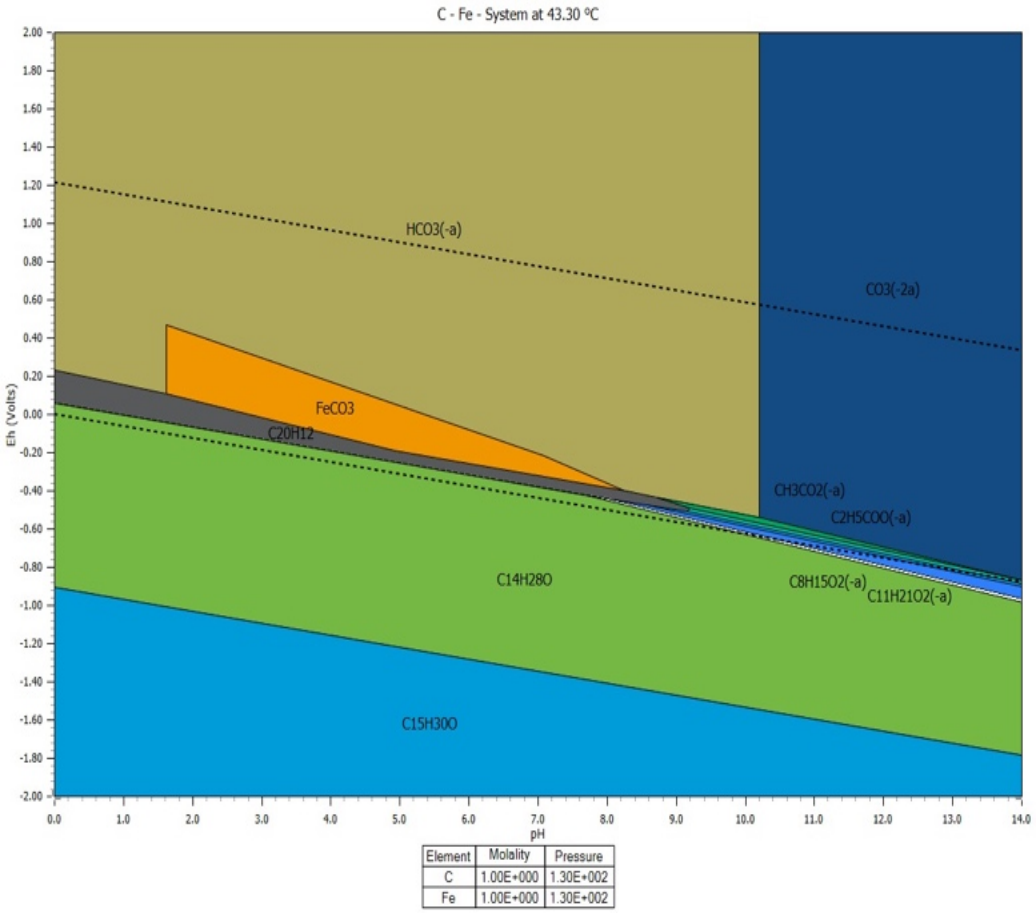

Figure 4.6. Eh-pH diagram of C-Fe at temperature of 43.3 °C and pressure of 130 bar.

With regards to Figure 4.7, at lower pH levels, the diagram shows the stability of pentadecane ($C_{15}H_{32}$), a hydrophobic organic compound, suggesting a system where organic carbon is present, perhaps indicating biological activity or petroleum contamination. As the pH increases, the stability field transitions to magnesium bicarbonate (Mg $(HCO_3)_2$ (aq)), a water-soluble complex typical in slightly acidic to neutral waters.

With further increase in pH, magnesium carbonate ($MgCO_3$) becomes the stable species. This is significant in geochemistry as $MgCO_3$ is a common mineral in sedimentary rocks and can influence water hardness and carbon sequestration in geologic systems. As the pH becomes highly alkaline, the diagram indicates that bicarbonate (HCO_3^-(aq)) and carbonate ions (CO_3^{2-}(aq)) are the predominant species. These anions play a crucial role in buffering systems and are key components in the geological alteration, affecting the alkalinity of natural waters and participating in the precipitation and dissolution of carbonate minerals.

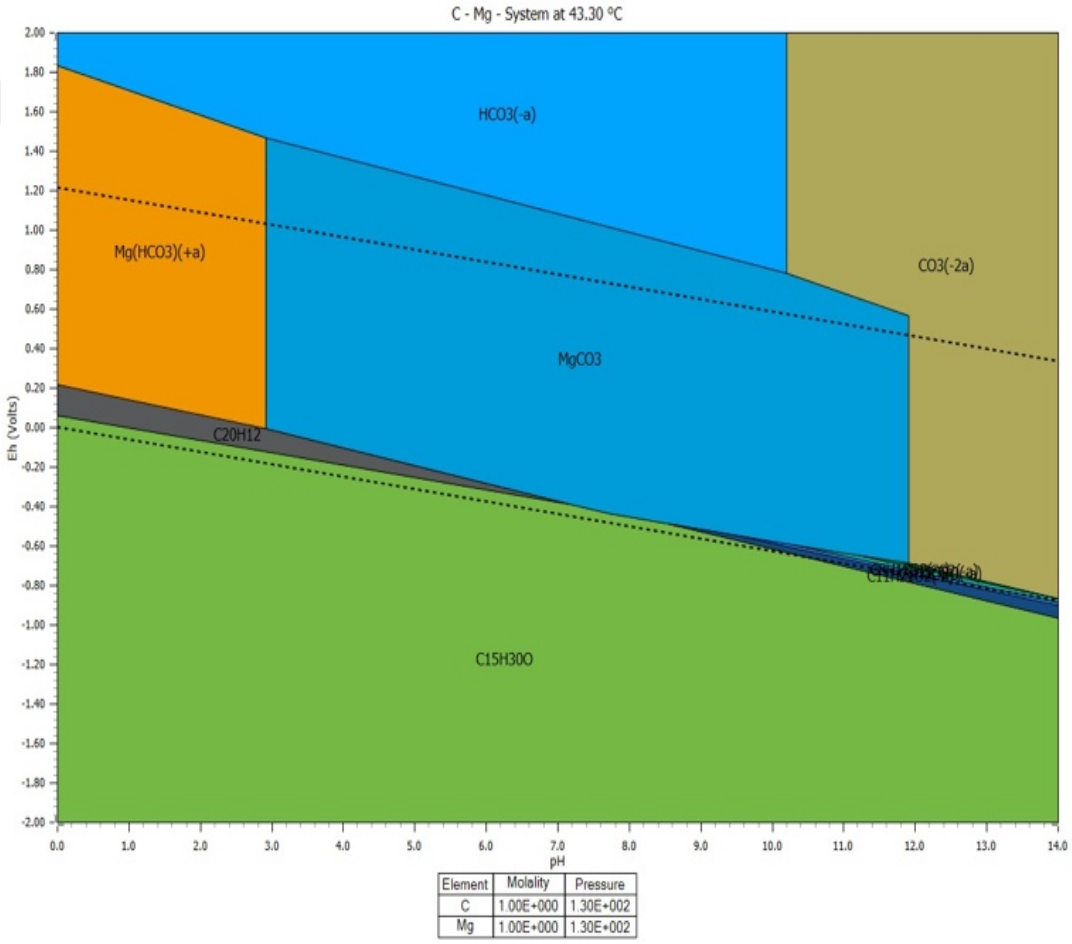

Figure 4.7. Eh-pH diagram of C-Mg at temperature of 43.3 °C and pressure of 130 bar.

4.1.1. Effect Of Permeability and Porosity

Generally, water and brine cling to mineral surfaces much more effectively than supercritical CO_2 does. If this is always the case, it has two major implications. First,

when CO_2 is forced into rock spaces, it doesn't completely kick out the existing brine. Instead, a thin film of brine is left behind on the mineral surfaces (referenced studies). If the area gets flushed with CO_2 repeatedly, this brine will eventually evaporate within the CO_2, leaving salt deposits on the rock. This could reduce permeability, a process called "salting." However, evidence suggests CO_2 flowing through the rock alters the mineral surfaces, potentially making them prefer CO_2 over time. Also, the brine's saltiness and the temperature affect the interaction between the brine, CO_2, and mineral surfaces.

The second consequence is due to the way CO_2 and brine interact with the rock, combined with their different surface tensions. This means high pressure is needed to displace the brine when injecting CO_2, especially in rocks with tiny pores. This also affects how effectively small CO_2 droplets get permanently trapped within the rock's pores.

Repeatedly flushing rock pores near the injection well with supercritical CO_2 can completely evaporate the existing brine, leaving salt deposits on the rock and potentially reducing its ability to flow fluids.

However, similar studies show CO_2 flow can alter the rock surfaces, making them prefer CO_2 over brine in some cases (Kim et al., 2012b). Additionally, factors like salt concentration (ionic strength) and temperature influence how strongly brine, CO_2, and the rock surface interact.

Figure 4.8. depicts a vertical cross-section of geological layers where the sandstone is sandwiched between two shale layers. The leftmost layer represents shale saturated with water (H_2O), followed by a central layer of sandstone saturated with carbon dioxide (CO_2), and finally, another layer of sandstone saturated with water (H_2O) on the right.

The ability of the shale caprock to retain supercritical CO_2 is a function of various geochemical and geophysical factors, including the permeability and porosity of the caprock, the density and viscosity of the CO_2, and the geochemical interactions between the CO_2, the brine, and the surrounding rock. The integrity of the shale caprock is crucial; it must be impermeable enough to prevent the upward migration of CO_2. Geochemically, reactions between the CO_2 and the surrounding minerals may lead to mineral trapping, further immobilizing the CO_2.

The variable 'h' likely represents the height of the CO_2 saturated section, which is a critical parameter when evaluating the storage capacity and security of a geological storage site. The taller the column of CO_2, the greater the pressure at the base, which may affect the solubility of CO_2 in the brine and the potential for CO_2 to escape through any weaknesses in the caprock. Understanding the dynamics illustrated in Figure 4.8 is essential for the risk assessment of CO_2 sequestration sites and for ensuring long-term storage stability, which is a significant concern for the feasibility of carbon capture and storage (CCS) as a climate change mitigation technology.

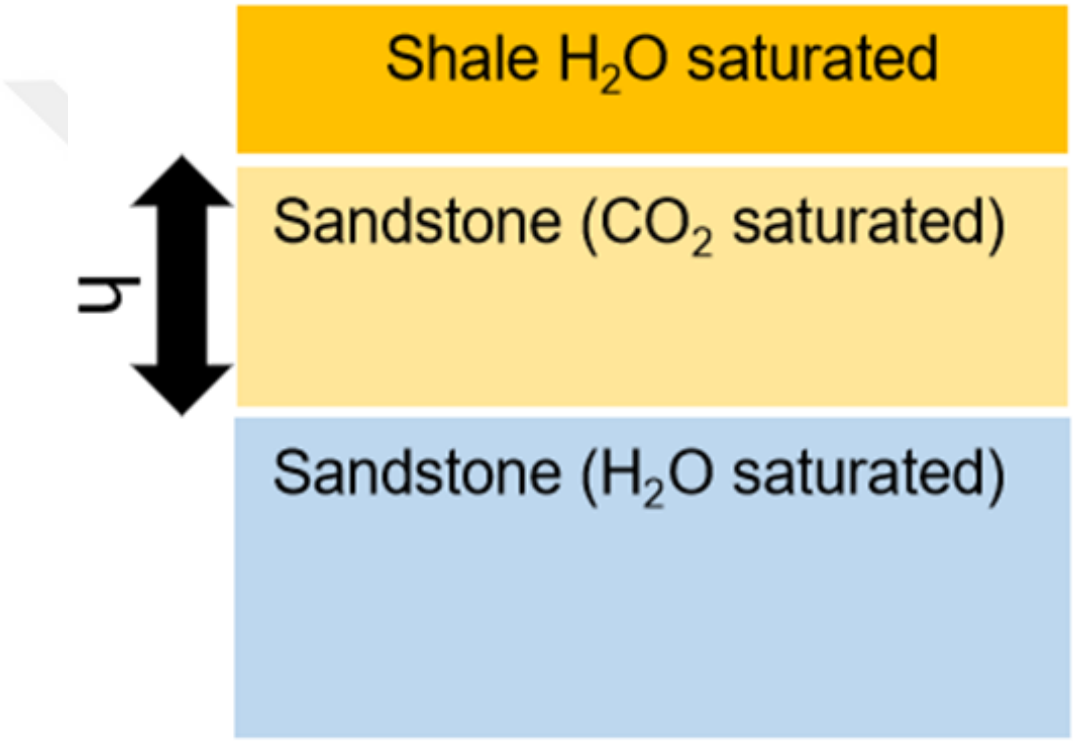

Figure 4.8. Dependence of column height of super critical CO_2 that can be maintained under a shale caprock.

The different interactions between CO_2 and brine, combined with their surface tension, often require high pressure to push CO_2 into small rock pores. This pressure also impacts how much CO_2 gets trapped within the pores.An essential consideration for enhancing subterranean carbon mineralization lies in the permeability and active porosity of the geological formation serving as the host rock. The presence of pores and fractures within these formations facilitates the movement of fluids, providing access to mineral surfaces that contribute cations essential for mineralization, as well

as offering space for carbonate precipitation. The total mass of carbon-bearing precipitates is influenced by the formation of secondary minerals, particularly clay minerals. These secondary minerals compete with carbonates for the divalent cations released from dissolving primary minerals, as well as for available pore space. Carbonate and associated secondary mineral precipitates typically occupy a greater volume than the primary minerals from which they originate. Consequently, they have the potential to obstruct fluid flow pathways by precipitating and/or sealing reactive surfaces. However, the expansion in volume during precipitation reactions can induce cracking and the opening of fractures, thereby enhancing permeability and exposing new surfaces to the fluid phase, which may facilitate subsurface carbonation. Additionally, it is important to recognize that due to the acidic nature of water-CO_2 solutions, mineral dissolution commonly occurs during injection, leading to the creation of pore space and flow paths near the injection well. The precipitation of pore-filling secondary minerals is anticipated to occur at a distance from the injection well once sufficient dissolution of the host rock has neutralized the acidic CO_2-rich injection fluids.

4.2. Evaluation Of Energy Consumption

The injection of CO_2 without water displays a different energy consumption with the situation when CO_2 is mixed in water with respect to the pressurization process. In the monophasic injection of CO_2, energy requirements escalate progressively in tandem with pressure increments, a phenomenon that is well-documented up to the critical juncture of 100 bar. In contrast, the biphasic injection involving a CO_2-H_2O mixture initially demands a higher energy input, even at lower pressures, as compared to the solitary CO_2 injection.

Another benefit of utilizing CO_2 injection as a water-dissolved gas is its potential to significantly reduce the cost of CCS. This is achievable through the direct capture of carbon dioxide and other acidic gases from CO_2-rich exhaust streams, which can be accomplished by mixing them with fresh water or seawater in a scrubbing tower. The energy required for pressurizing CO_2-charged water to pressures of up to 140 bar is also minimized.

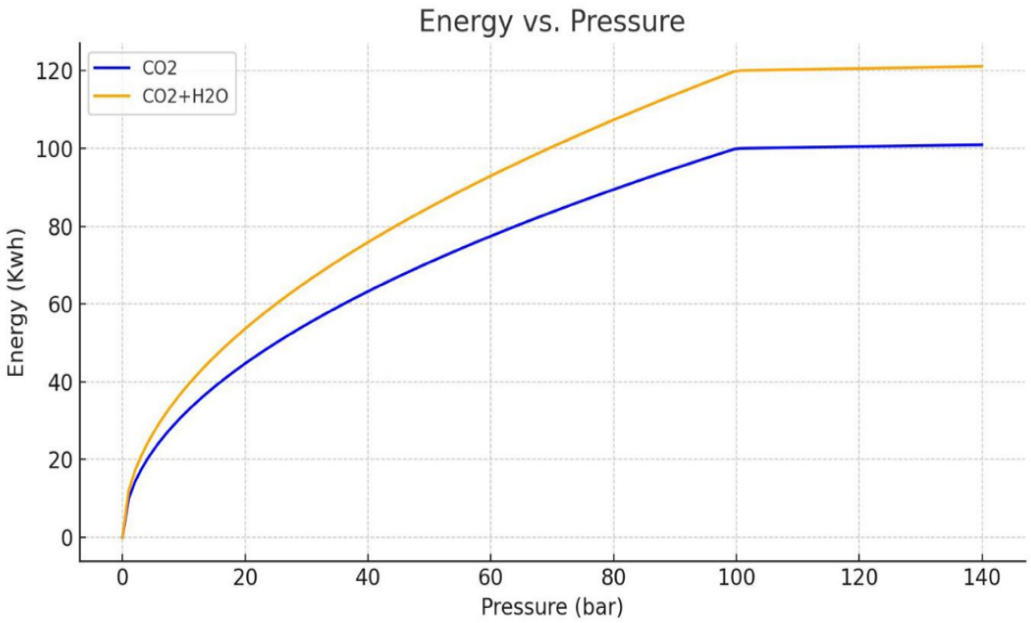

Figure 4.9. Energy consumption comparison between monophasic CO_2 injection and biphasic CO_2-H_2O injection.

4.2.1. Risk assessment.

The simulation model was designed to examine the dynamic evolution of a geological CO_2 storage reservoir's properties over a ten-year period, anchoring the initial conditions in empirical data. The initial porosity was empirically set at 27%, typical of a highly porous sandstone reservoir suitable for CO_2 sequestration. Permeability was similarly established in 1700 millidarcies (md), reflecting the reservoir's initial capacity for fluid flow. These starting values are not hypothetical but are derived from factual, baseline measurements.

To simulate the potential impact of sustained CO_2 injection, we modeled a non-linear decrease in porosity, decreasing to 22%, and a gradual reduction in permeability to 1550 md over the course of the decade. These changes are based on predictive modeling of the expected geological response to CO_2 injection, such as mineral precipitation and the compaction of the reservoir structure, which could lead to a reduction in both porosity and permeability.

The MATLAB-based simulation integrated these projected changes to assess their cumulative effect on CO_2 storage capacity. It is modeled the storage capacity as a variable that would inherently decline in tandem with reductions in porosity and permeability. The computational power and graphical capabilities of MATLAB were

instrumental in visualizing the data, enabling an in-depth exploration of the interrelated changes within the reservoir.

While the simulation is grounded in a synthesis of the current data and geological understanding, it is acknowledged the inherent complexities and uncertainties of subsurface environments. Consequently, the model should be interpreted as an advanced approximation, providing critical foresight into the potential trajectories of CO_2 storage characteristics. This foresight is essential for the strategic planning and adaptive management of CO_2 sequestration operations, ensuring they remain effective and safe over the long term.

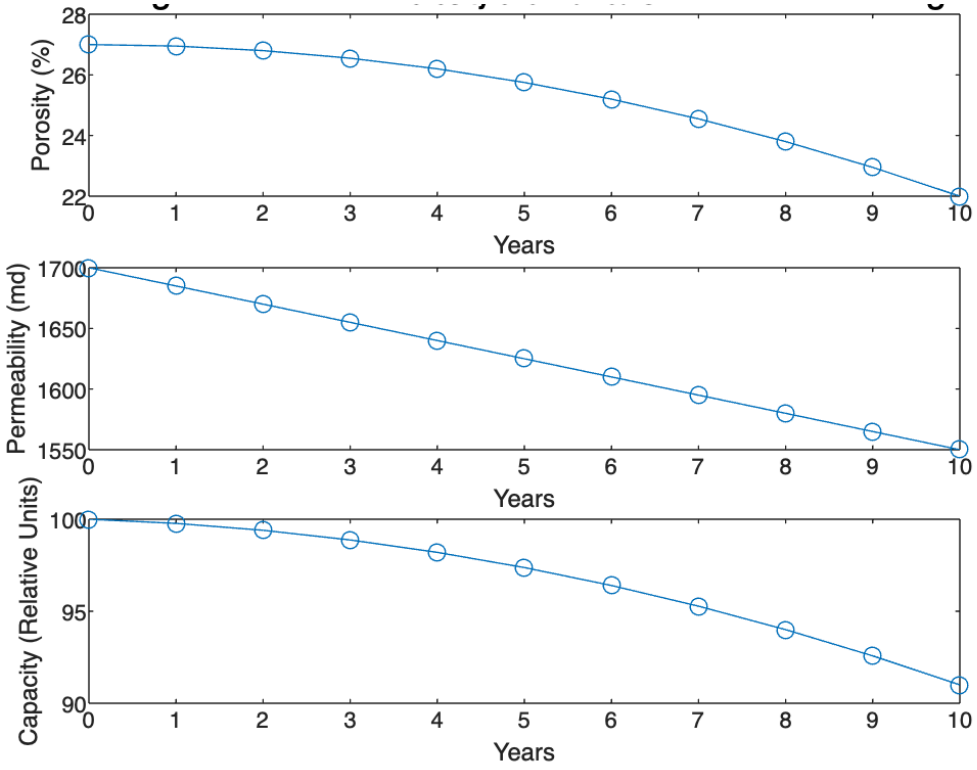

Figure 4.10. Decadal simulation of CO_2 sequestration reservoir properties.

The provided plot illustrates the escalating energy requirements for the injection of CO_2 into a geological storage reservoir over a ten-year period, as predicted by our MATLAB simulation model. The energy requirement, expressed in kilowatt-hours (kWh), is observed to follow an upward trend, starting from approximately 3.5×10^{-4} kWh in the first year and increasing to just over 6.5×10^{-4} kWh by the tenth year. This increment reflects the compounding effects of reduced reservoir permeability and porosity, which necessitate higher injection pressures to maintain the designated CO_2

injection volumes. In alignment with the simulated conditions, we assumed a starting pump efficiency of 95% which experiences a marginal annual decline, and an energy cost per unit of pressure that grows by 2% each year to accommodate the heightened resistance within the reservoir. The trend is nearly linear, suggesting a consistent rate of change in the factors affecting energy requirement, such as the mechanical properties of the reservoir and the operational efficiency of the injection system. These simulation results underscore the importance of accounting for increased operational costs over time in the strategic planning of long-term CO_2 sequestration projects. The model provides a valuable foresight into the energy dynamics of CO_2 injection processes, enabling stakeholders to make informed decisions about resource allocation, economic feasibility, and the sustainability of CO_2 storage solutions.

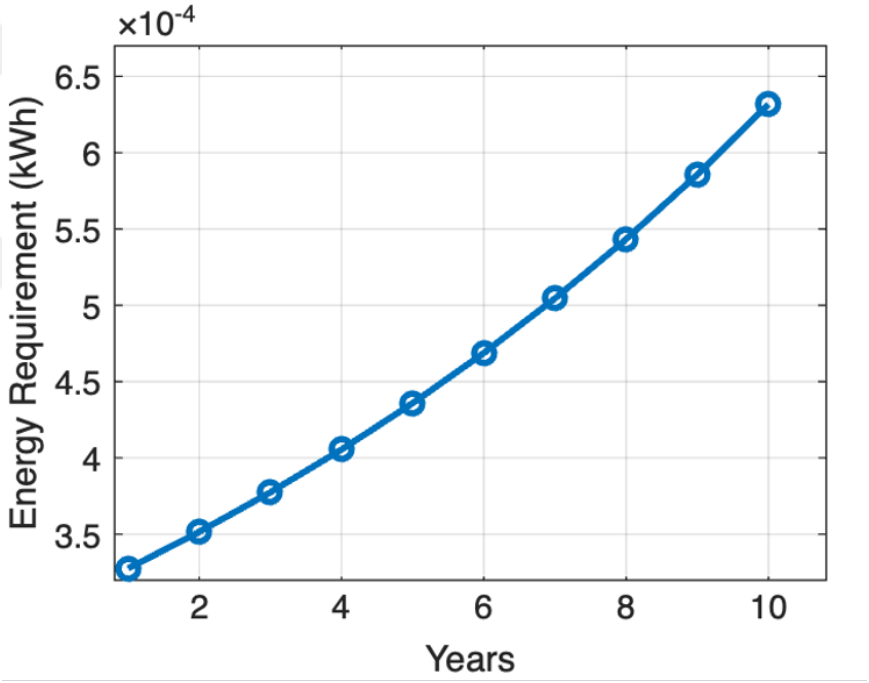

Figure 4.11. Increasing energy demands for CO_2 injection.

The potential leakage of stored CO_2 from geological reservoirs poses significant environmental concerns, particularly in the context of climate change mitigation efforts. The simulation model we developed in MATLAB considers the dynamic evolution of the reservoir's porosity and permeability over a decade to assess the risk of CO_2 leakage. The model indicates a gradual increase in leakage probability, initially set at a 1% risk and rising annually due to the compounding effects of increased pressure buildup, which is inversely proportional to the decreasing permeability and

porosity. This elevated risk underscores the criticality of continuous monitoring and robust engineering controls to prevent leakage, which could not only negate the benefits of sequestration but also pose risks to groundwater quality and contribute to greenhouse gas emissions. The visualization of leakage risk through this model illuminates the importance of strategic reservoir management and the implementation of early detection systems to mitigate environmental impacts. While the simulation provides a theoretical projection, it serves as a vital tool in highlighting areas where proactive measures and adaptive strategies are necessary to ensure the integrity and success of CO_2 storage projects.

The risk assessment studies shows that the 450-bore penetration at the Bell Creek Oil Field could be potential hazards to cause the leakage of CO_2 to the upper surface. The early risk like this can be identified by sampling and analysis of soil, gas, surface water and ground water. The physical parameters like pressure monitoring at the operational injection wells and production oil wells gives the idea about the fracturing or leakage hazards and bore problems. The risks can be managed by taking steps of corrective actions.

The migration of liquids to wrong pathways will also be studied from secondary sources to conduct the potential hazards and risk assessment from targeted storage site for CO_2. The migration of CO_2 from the injection facility in both vertical and horizontal direction could cause financial and safety damages to the project. The study of CO_2 pathway migration is necessary as it doesn't take part in the enhanced oil recovery rather is considered as wastage of resources and being inefficient. The identification of CO_2 migration pathway is difficult to identify and also the ultimate destination of CO_2, but it is considered as loss of resources.

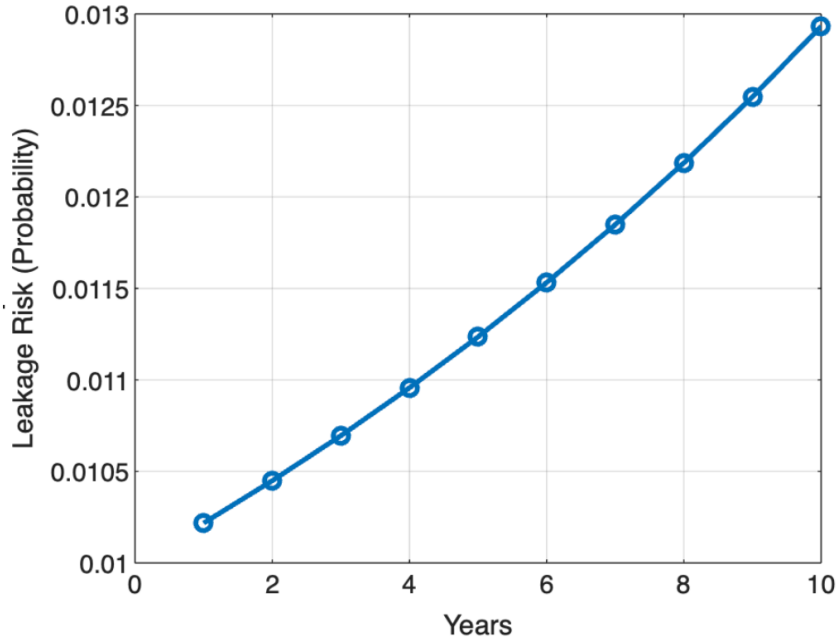

Figure 4.12. Projected increase in CO_2 leakage risk over time.

The MATLAB-generated graph delineates the comparative energy requirements for two distinct methodologies of carbon dioxide (CO_2) injection over a period of ten years. The red line represents the scenario of injecting CO_2 without water, and the blue line represents the scenario where CO_2 is injected along with water.

Observing the graph, it is apparent that both energy requirements exhibit a linear increase over time. In the initial year, the energy requirement for injecting CO_2 without water is approximately $3.63.5 \times 10^{-4}$ kWh, whereas CO_2 injection with water starts at a slightly higher energy requirement of approximately 4×10^{-4} kWh. This indicates that the process of dissolving CO_2 in water requires additional energy at the outset.

As the years progress, the energy requirement for both methods escalate linearly. By the end of the tenth year, the energy requirement for CO_2 without water advances to approximately 4.8×10^{-4} kWh, and for CO_2 with water, it reaches about 5.2×10^{-4} kWh. The data reveals a consistent annual increase, with the energy requirement for CO_2 without water growing at a rate of 0.12×10^{-4} kWh per year, and the CO_2 with water method exhibiting a slightly higher growth rate of 0.12×10^{-4} kWh per year.

This linear trend suggests a steady decline in reservoir permeability and porosity, necessitating an incremental rise in injection pressures to sustain the designated CO_2 injection volumes. The simulation has factored in the gradual decline in pump

efficiency, which starts at 95% and decreases marginally each year. Additionally, the energy cost per unit of pressure is assumed to amplify by 2% annually to account for the increased resistance encountered within the reservoir.

These results underscore the significance of energy considerations in the strategic planning of CO_2 sequestration projects. They provide insight into the operational costs, highlighting the importance of including energy requirement forecasts in the financial planning and sustainability assessment of long-term CO_2 storage initiatives.

In conclusion, the energy requirements for both CO_2 injection methods are projected to increase linearly over a decade, with CO_2 injection with water consistently consuming more energy than CO_2 without water. The simulation outputs are essential for stakeholders who need to evaluate the long-term economic and environmental viability of CO_2 sequestration methods.

To address the risk of leaks, the use of CO_2-charged water is advantageous due to its higher density compared to CO_2-free water. However, a significant drawback of this method is the substantial amount of water required to dissolve the CO_2 gas. Nevertheless, this water could potentially be extracted from the target reservoir itself, offering an avenue for monitoring the chemistry of the injected gas-charged fluid and averting reservoir pressure escalation resulting from injection.

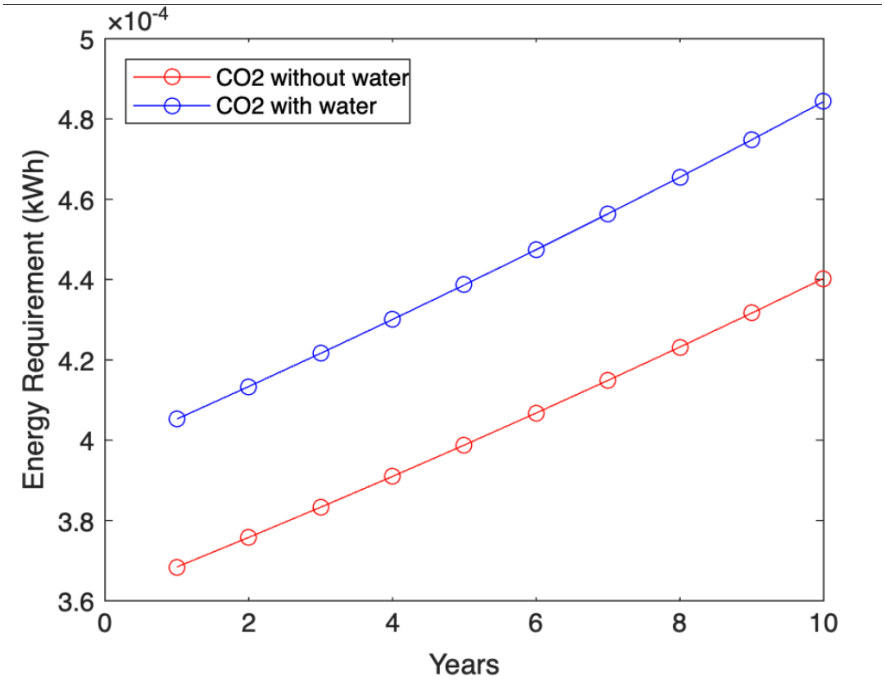

Figure 4.13. Comparative energy requirements for CO_2 injection methods.

The provided graph represents a comparative analysis of the energy requirements for two methods of CO_2 injection into a geological storage reservoir over a ten-year period, based on simulations conducted using MATLAB. There are two scenarios are considered:

1. The red line traces the energy cost for injecting CO_2 without water (Scenario A)
2. The blue line illustrates the energy cost for injecting CO_2 with water (Scenario B).

Both lines exhibit a linear upward trend, indicating a steady increase in energy requirements over the years.

In the initial year, the energy cost for Scenario A begins at a lower value compared to Scenario B. However, as time progresses, both scenarios show a consistent yearly increase in energy costs. By the tenth year, the energy cost for Scenario A has increased by an amount that is slightly less than that of Scenario B, which starts at a higher value and maintains a consistent annual growth rate. The close parallel between the two lines suggests that the additional energy required to dissolve CO_2 in water at the outset (evident in Scenario B) remains relatively constant over time.

The linear nature of the increase in energy costs for both scenarios likely reflect the compounding effects of decreasing reservoir permeability and porosity. As the reservoir's physical characteristics change—likely due to factors such as mineral precipitation and compaction—higher injection pressures are required to achieve the same volume of CO_2 injection, thereby increasing energy demands. The simulation also likely assumes a marginal decline in pump efficiency and an annual increase in the cost of energy per unit of pressure, which would contribute to the overall rise in energy requirements.

Figure 4.14 provides a detailed visual representation that is vital for stakeholders when evaluating the viability and economic impacts of CO_2 sequestration methods over an extended period. It showcases a comparative cost analysis of two distinct CO_2 injection strategies, spanning a decade. The graph indicates two trajectories: the cost for Scenario A, which is CO_2 injection without water, represented by a red line with circle markers, and the cost for scenario B, which is CO_2 injection with water, delineated by a blue line with circle markers. This underscores the significance of incorporating the

progression of operational costs into the assessment of long-term sustainability. Notably, despite a higher initial expenditure associated with CO_2 injection with water (Scenario B), the graph suggests that the incremental cost over time aligns closely with that of the waterless method (Scenario A). This convergence implies that the long-term difference in energy and financial requirements between the two methods could be relatively insignificant. The initial steep slope for Scenario B may reflect the enhanced energy demands and infrastructure required for water-assisted CO_2 injection, but this difference diminishes over time.

Stakeholders are presented with a strategic decision-making tool through this graph. They can weigh the immediate and higher costs of CO_2 injection with water against the anticipated advantages, such as improved CO_2 solubility, which could lead to more efficient sequestration, and potentially lower risks of leakage, thereby enhancing environmental security. These factors could contribute to the overall cost-effectiveness of the CO_2 sequestration project.

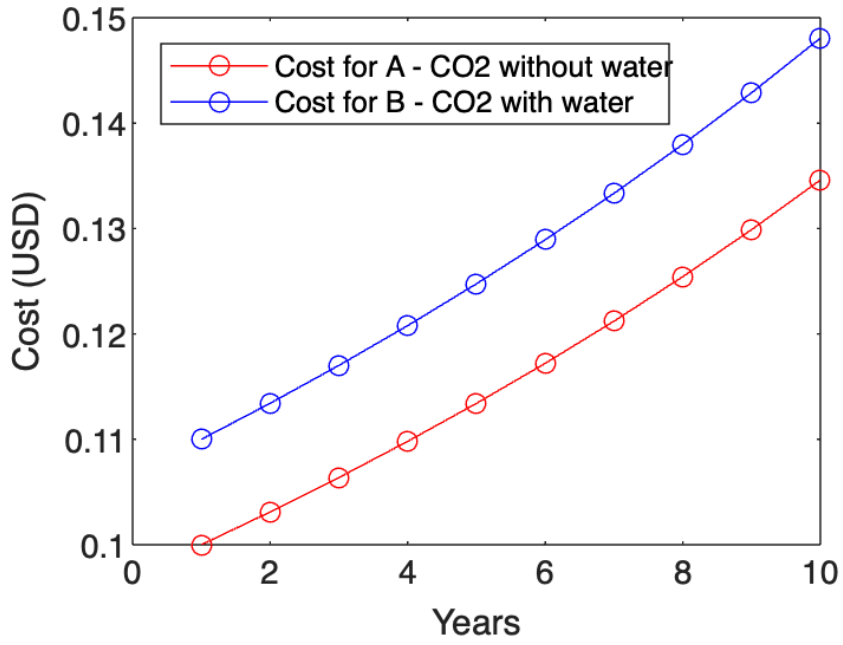

Figure 4.14. Cost analysis for two scenarios of CO_2 injection methods over a decade.

In essence, Figure 4.14 is not just a depiction of cost but a nuanced tool for projecting and planning the future of CO_2 sequestration technologies. It provides a data-driven

foundation for policymakers, industry leaders, and environmentalists to formulate informed strategies that harmonize fiscal responsibility with ecological stewardship, particularly in the realm of carbon management and climate change mitigation.

5. CONCLUSION

The culmination of this master's thesis in the exploration of CCS within the Bell Creek Oil Field presents a multifaceted analysis encompassing geological, environmental, and energy consumption criteria. This investigation has elucidated the intricate interplay between geochemical alterations induced by CO_2 storage and their subsequent effects on crucial geological parameters such as porosity, permeability, and leakage potential. This conclusion of these findings highlights the implications for CCS feasibility, sustainability, and the overarching goal of mitigating climate change impacts.

The research has meticulously documented how the injection of CO_2 into the Bell Creek Oil Field initiates geochemical processes that markedly influence the structural integrity of the storage reservoir. Geochemical reactions, such as the dissolution of silicate minerals and the formation of carbonate minerals, play a pivotal role in the long-term stability and capacity of the reservoir for carbon sequestration. These processes, while contributing to the mineral trapping of CO_2, also have the potential to alter porosity and permeability, impacting fluid flow dynamics and the efficiency of CO_2 storage. The nuanced understanding of these geochemical interactions underscores the need for careful selection of injection sites, emphasizing geological formations with favorable characteristics for CO_2 mineralization and storage integrity.

The evaluation of data shows that the dissolution of CO_2 in water during CCS in Bell Creek Oil field wells causes the formation of weak carbonic acid. This HCO_3^- ion reacts with the minerals presented in the reservoir and causes carbonization of some species such as Ca, Mg, Na, and Fe. This geochemical alteration will decrease the permeability from 1700 to approximately 1550 dm within 10 years and decrease the porosity from 27% to 22%. This will influence the capacity of the reservoir. Consequently, the energy consumption for CO_2 injection will increase from 3.25×10^{-4} kWh to 6.37×10^{-4} kWh.

In addition, the leakage risk will be increase from 1.01% to 1.3% from the first year of injection and after 10 years, respectively. Another simulation related to the comparison of the injection of CO_2 without and with water shows that the pressure needed for the injection of CO_2 mixed with water needs lower pressure and less energy consumption. But it may have some tow fold effect on the energy consumption. By enough amount of water in the injected CO_2, energy usage will decrease approximately 11.44% during the injection period, as a negative effect it can promote the geochemical reaction, specifically the carbonization process and decreased the permeability and porosity.

The study has rigorously evaluated the energy requirements associated with CCS operations, revealing a nuanced relationship between the technological needs for CO_2 injection and the operational efficiency. The simulation results, facilitated by MATLAB, have provided valuable insights into the escalating energy demands over time, necessitated by changes in reservoir characteristics such as decreasing porosity and permeability. This analysis is crucial for forecasting the long-term sustainability and economic viability of CCS projects, underscoring the importance of integrating energy efficiency measures and innovative technologies to optimize CCS operations.

Through a detailed examination of the environmental implications of CCS, this research has highlighted the critical importance of continuous monitoring and robust engineering controls to mitigate the risk of CO_2 leakage. The potential environmental impacts, including the risk to groundwater quality and unintended greenhouse gas emissions, necessitate a proactive approach to reservoir management and leakage prevention. The findings advocate for the deployment of early detection systems and the development of adaptive strategies to ensure the integrity and success of CCS projects in contributing to climate change mitigation.

Although the advancement in this technology, there are risks involved in the CCS project and lessons also indicates that more research and development is needed in the field of carbon capturing, mobilization, injecting it and storage into the sub-surface without polluting the underground natural resources and aquifers.

Considering the detailed findings and insights gained from this investigation into CCS at the Bell Creek Oil Field, it is imperative to propose strategic recommendations that

could enhance the effectiveness, sustainability, and safety of CCS projects, not only within the scope of this study but also in broader applications. These recommendations are derived from the critical evaluation of geological, environmental, and energy consumption aspects of CCS, emphasizing the need for an integrated approach to optimize CCS implementation and management.

1. **Advanced Geochemical Monitoring:** To address the complexities of geochemical alterations and their impacts on reservoir characteristics such as porosity and permeability, it is recommended that CCS projects incorporate advanced geochemical monitoring systems. These systems should be capable of real-time analysis to promptly detect changes in mineral composition and fluid dynamics within the reservoir. This proactive monitoring is crucial for anticipating and mitigating adverse effects on storage capacity and integrity.
2. **Enhanced Risk Management Strategies:** The incremental increase in leakage risk over time underscores the necessity for robust risk management strategies. It is advisable to develop and implement comprehensive leakage prevention and detection protocols, including the use of advanced sensing technologies and predictive modeling tools. These measures should be complemented by regular environmental impact assessments to ensure the long-term safety and viability of CCS projects.
3. **Optimization of CO_2 Injection Processes:** The research has highlighted the significant energy demands and operational challenges associated with CO_2 injection. To optimize these processes, future projects should explore the integration of renewable energy sources to power injection operations. Additionally, innovations in injection technology that improve CO_2 solubility and dispersion within the reservoir can contribute to reducing energy consumption and enhancing storage efficiency.
4. **Water Management in CCS Operations:** Given the dual role of water in facilitating CO_2 injection and potentially exacerbating geochemical reactions, careful management of water resources is essential. It is recommended that CCS operations employ strategies for water recycling and minimization of freshwater usage. Moreover, the injection of CO_2 -charged water should be optimized to balance the benefits of reduced energy requirements against the risk of accelerated geochemical alterations.

5. **Collaboration and Knowledge Sharing:** CCS is a rapidly evolving field that benefits significantly from interdisciplinary collaboration and knowledge sharing. Establishing partnerships among academic institutions, industry stakeholders, and government agencies can foster innovation and accelerate the development of best practices for CCS. Sharing experiences and challenges from different CCS projects will contribute to a collective understanding and improvement of CCS technologies and methodologies.
6. **Policy and Regulatory Frameworks:** To support the advancement and deployment of CCS technologies, it is crucial to develop and implement supportive policy and regulatory frameworks. These frameworks should encourage research and development in CCS, provide financial incentives for CCS projects, and establish clear guidelines for environmental protection and safety. Engaging policymakers in dialogue about the benefits and challenges of CCS can facilitate the creation of regulations that promote sustainable and responsible CCS implementation.
7. **Future Research Directions:** Finally, the findings from this thesis highlight several areas for future research, including the exploration of novel materials and technologies for CO_2 capture, the development of more efficient CO_2 injection techniques, and the investigation of alternative geological formations for CO_2 storage. Further studies are also needed to assess the long-term impacts of CCS on ecosystems and groundwater resources, as well as to explore the socio-economic implications of CCS deployment on local communities and industries.

By adhering to these recommendations, CCS projects can navigate the complexities and challenges identified in this thesis, moving closer to realizing their potential as a pivotal technology in the global effort to mitigate climate change. The integration of these strategies will not only enhance the effectiveness and sustainability of CCS but also contribute to the broader goal of achieving a carbon-neutral future.

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CURRICULUM VITAE

Name Surname : Mohammadreza JABBARI SAHEBARI

EDUCATION :

- **B.Sc. :** 2016, Islamic Azad University Tabriz, Faculty of Engineering, Department of Geology Engineering
- **M.Sc. :** 2024, Istanbul Technical University, Faculty of Mine, Department of Civil Engineering

PROFESSIONAL EXPERIENCE AND REWARDS:

- 2013-2015 Participated in various research projects including waste treatment analysis, groundwater modeling, and tree fiber strength tests.
- 2014-2015, at Moghavem Shalode Behine Co., Iran. Held the position of Laboratory Technician, engaging in concrete testing and evaluation.
- 2017-2018, at Saruj Banaye Azerbaijan Co., Iran. Worked as a Technical Office Engineer, specializing in water resources modeling and drought threat assessment.
- 2018-2019, at Saruj Banaye Azerbaijan Co., Iran. Served as a Supervisor Engineer, where I managed agricultural water distribution systems and implemented pressurized irrigation systems.
- 2022 Completed certifications including "Learning for a Sustainable Future: Live at COP26" and "Bushfires: Response, Relief, and Resilience. "

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Jabbari Sahebari, M. ,** 2023. Effect of Geological and Geomorphological Factors on Gotvand Dam Water Quality. Water Resources Journal, Springer, January 2023. (DOI: 10.1134/S0097807823600055).
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